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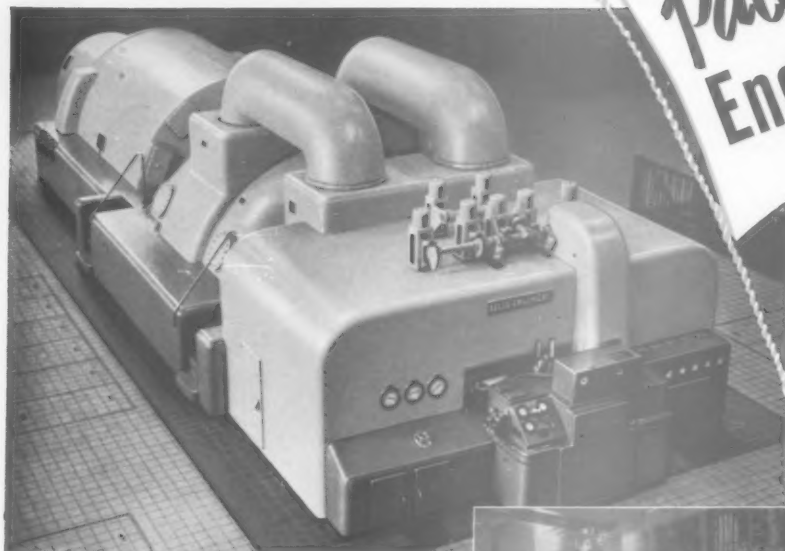
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Electrical **REVIEW**



ALLIS-CHALMERS STEAM-TURBINE Generator Units

For Pace-Setting Engineering

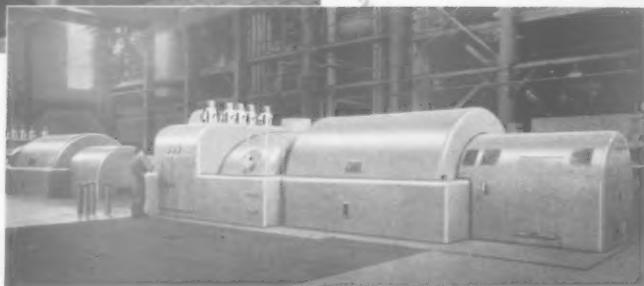


World's first supercharged hydrogen-cooled generating unit — rated 60,000 kw — completed first calendar year of commercial operation with 100% availability record and 97.41% on-the-line service factor. Supercharged cooling permits smaller plant size, foundation savings and many other advantages.

WHETHER YOU REQUIRE a 200,000-kva central station turbine-generator unit or a small industrial unit, you can turn to Allis-Chalmers for the engineering advances that count.

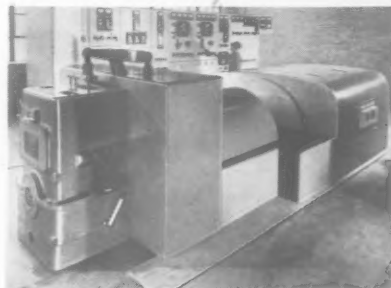
Supercharged hydrogen cooling of generators . . . simplified hydrogen seal and control . . . world's lowest exhaust pressure turbines . . . solidly bolted down steam end pedestal . . . 825 F reheat turbine in 1935 — these are some of the A-C *firsts* in turbine-generator development.

With units up to 173,000 kva in successful operation, A-C supplies a complete line of condensing, non-condensing and automatic extraction turbines—and matching surface condensers. The bulletins listed below — and your A-C representative — can help to show you why you will gain most by specifying Allis-Chalmers units.



These recently installed 20,000-kw, 3600-rpm turbine-generator units are representative of the 20,000 and 30,000-kw single-cylinder design conforming to AIEE-ASME preferred standards.

WA-Series turbine-generators, such as this 2500-kw unit, are built in sizes 2000 kw and larger in NEMA standard ratings. This series combines impulse turbines with housing-type air-cooled generators in a compact three-bearing arrangement.



A-4141A

CHECK THIS BULLETIN LIST

25B6150 — Power Equipment
19B6784 — Surface Condensers
03B6801 — Standardized Steam Turbines

03B7654 — WA-Series Steam-Turbine Generator Units

05B7773 — *Supercharged* Cooling of Generators

ALLIS-CHALMERS

Milwaukee 1, Wisconsin



ALLIS-CHALMERS **Electrical REVIEW**

THE COVER

BIG IN HORSEPOWER—small in diameter—this stator is for one of the largest two-pole synchronous motors ever built. Skilled workmen are inserting slot sticks in this 3600-rpm machine which, when installed at the Arnold Engineering Development Center, Tullahoma, Tennessee, will provide 36,000 of the 129,500 total main-drive horsepower being supplied together with compressors to provide the huge volume of air consumed in testing ram-jet engines.

*A-C Staff Photo
by M. Durante*

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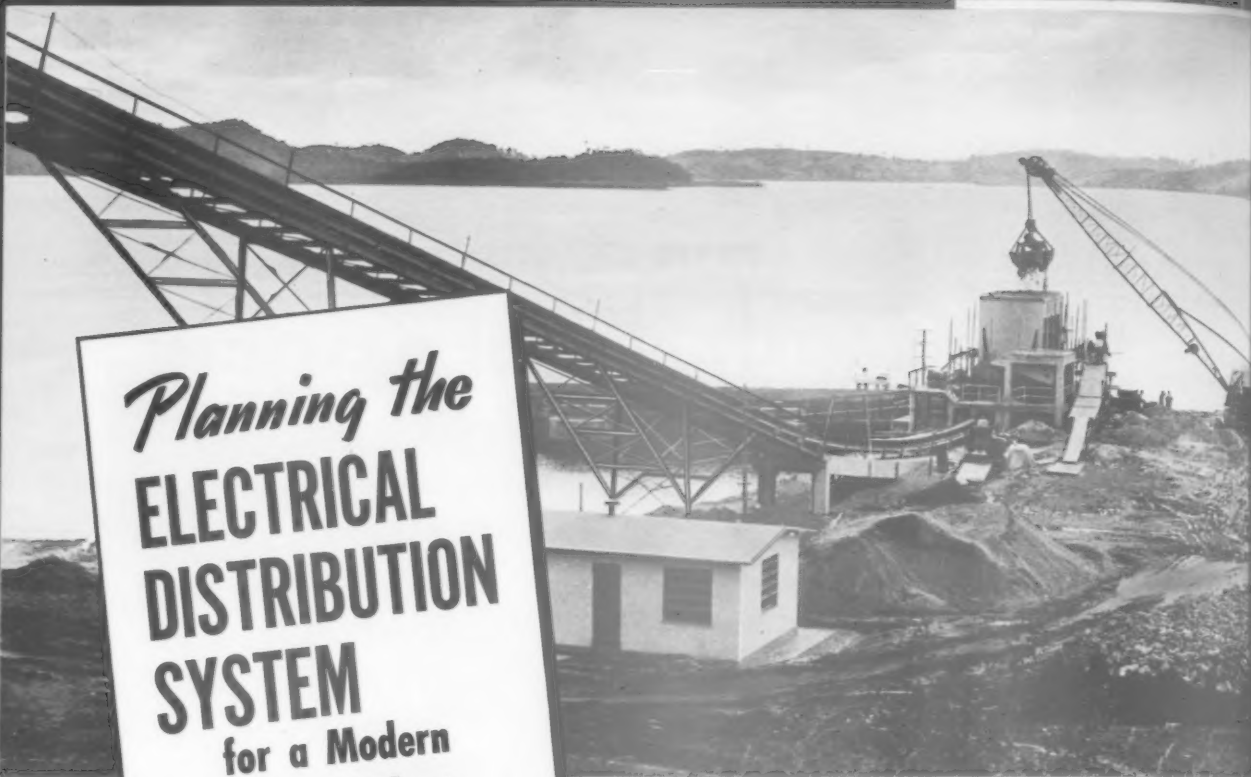
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Planning the ELECTRICAL DISTRIBUTION SYSTEM for a Modern Cement Plant



by **C. L. KLEEMANN**
Switchgear Department
Allis-Chalmers Mfg. Co.

The yardstick for determining voltages and equipment in this new processing plant was a high standard of reliability.

ON THE SHORE OF BRAZIL'S BAY OF BAHIA is a new processing plant using coral sand as the principal ingredient for the manufacture of cement. This plant, entirely new from top to bottom, presented many problems during its design stages. One of them was the design of its electrical plant and distribution system.

Before the electrical system could be designed, its required capacity had to be determined. In deriving the sustained maximum power required by the entire plant, the power needs of all equipment in use during the period of greatest load was totaled and found to be 70 percent of the total connected load. This figure compared favorably with the demand factor for most cement plants. Although the percent of connected load in use when power require-

ment is maximum may differ slightly from one plant to another — because of the ratio between spare motors and motors in normal operation, the relationship of motor size to horsepower requirements of the driven machine, plant operational procedure or other variables — it almost always approximates 70 percent.

The connected load of this plant is approximately 5295 hp, with 3897 hp required during the periods of greatest load. Of this total, 1267 hp is required by the small motors, 230 hp for dc motors and synchronous motor excitation, and 2400 hp for the large motors driving processing machinery. Assuming that average efficiency is 80 percent for small motors and dc equipment, and 92 percent for the large ball mill motors, the total load amounts to 3350 kw for the period. Because ball mills are operated at leading power factor, the power factor of the load supplied by the generators will approximate unity. To supply this load two 1875-kva generators were deemed adequate.

Selecting generator voltage

First, consideration was given to 600 volts corresponding to a standard motor voltage of 550 volts. However, resulting short circuit currents would be high. For instance, excluding motor feedback from motors in operation, available short circuit current from each generator with neutrals grounded would approximate 37,500 amperes. Should future expansion be warranted, doubling of the generating capacity would produce short circuit currents higher than can be interrupted with presently available circuit breakers. Since future plant growth is a definite possibility, no further consideration was given to generation at 600 volts.

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Higher voltages were then considered, and 2400 volts was rejected in favor of 4160 volts, for the following reasons:

A breaker rated 100,000-kva interrupting capacity at 2400 volts will interrupt 150,000 kva at 4160 volts. In view of probable future expansion, the higher interrupting capacity is desirable.

If the lower voltage were selected, switchgear having larger, more costly breakers would be necessary in view of ultimate requirements. Thus the same breaker at higher operating voltage becomes the more economical installation. At the lower voltage, motors and generators are less costly, but control equipment is higher priced. At the higher voltage, the saving in control equipment is offset by more costly motors and generators. Therefore, one consideration offsets the other.

Another consideration in determining generator voltage was voltage drop in the cables. The percentage drop is much less at 4160 volts than at 2400 volts. If the same size cable were used in both cases, voltage regulation would be inversely proportional to the square of the voltage. Actually, smaller size cable is used at 4160 volts since cable reactance is approximately the same; and even with the higher resistance, regulation remains nearly inversely proportional to the square of the voltage. Furthermore, some savings result from the use of smaller conductors.

In addition, better regulation is obtained at 4160 than at 2400 volts. This assures closer to rated voltage at equipment and better motor operation, since the torque a motor develops is directly proportional to the square of voltage. Induction motors have improved starting and stalling torque characteristics and less slip at correct voltage than at reduced voltage. Synchronous motors also have higher starting torque, pull-in torque and pull-out torque when operated at rated voltage rather than reduced voltage.

Also, at this higher voltage, there is less danger of motor controllers disconnecting machines from the line because of voltage fluctuations caused by switching and starting loads.

Next, consideration was given to potentials above 4160 volts. Standard voltages of 4800 and above require

switchgear and control equipment of the 15-kv insulation class. The control equipment, the switchgear, the motors, and the generators would all be more costly at a higher voltage. With the amount of power used by this installation, voltage regulation at 4160 volts will be satisfactory and cable sizes relatively small. The additional cost for going to a voltage higher than 4160 volts would greatly outweigh any advantages that could be obtained. Therefore, 4160 volts was selected. Figure 1 shows one of the two 1875-kva, 4200-volt generators, together with the 2200-hp diesel engine which drives it.

Selection of motor voltages

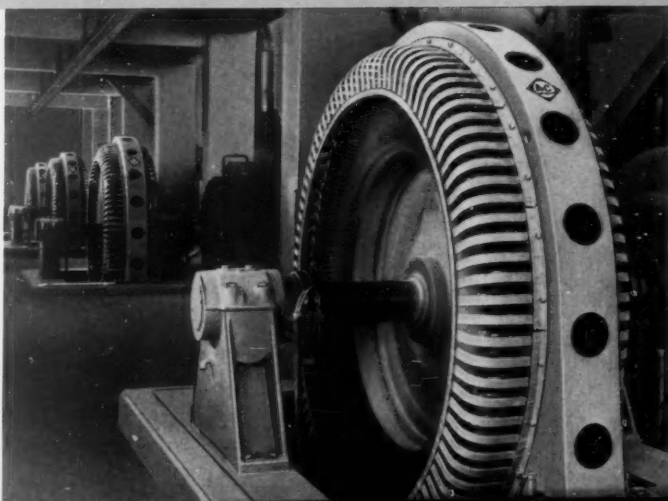
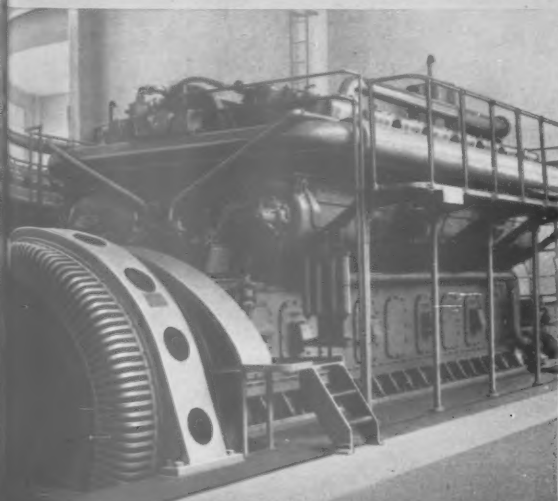
Consideration was given to both operating characteristics and economy before selecting the generating voltage of 4160 as the operating voltage for the four ball mill drive motors. Two motors drive ball mills for raw grinding, the other two drive ball mills for finish grinding. All four are identical 600-hp, 200-rpm, three-phase synchronous machines.

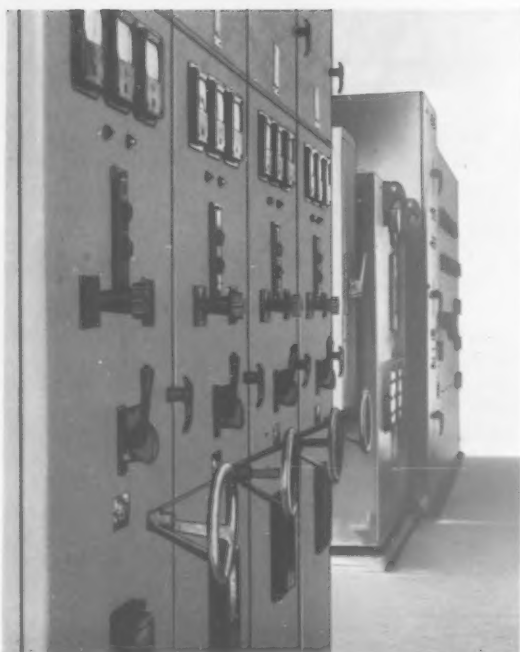
Economy favored the selection of 4160 as the motor voltage. The additional cost of step-down transformers would more than offset the cost differential between a 4160-volt motor and a motor of lower voltage. Also, control equipment for 4160 volts is less costly.

An analysis of this system showed that momentary undervoltage resulting from inrush current when a ball mill drive motor started under no load was not objectionable. Sufficient starting torque would be developed. Therefore, across-the-line motor starters were provided, since they are less costly than reduced voltage starters. However, the generating system is not large enough to permit starting these motors under load; consequently magnetic clutches were provided between the motors and ball mill shafts. Each motor is started with the clutch disengaged. The clutch is energized by means of a starter button on the magnetic clutch controller after the motor pulls into synchronism. To protect against exceeding pull-out torque, a load relay in the magnetic clutch controller operates from a current transformer located in a corresponding 4160-volt motor controller. This load relay automatically

POWER FOR THE ENTIRE PLANT is supplied by two 1875-kva, 0.8 pf, 300-rpm, three-phase diesel-driven generators. (FIGURE 1)

BALL MILLS are driven by these four 600-hp, 200-rpm, 4160-volt synchronous motors through magnetic clutches. (FIGURE 2)





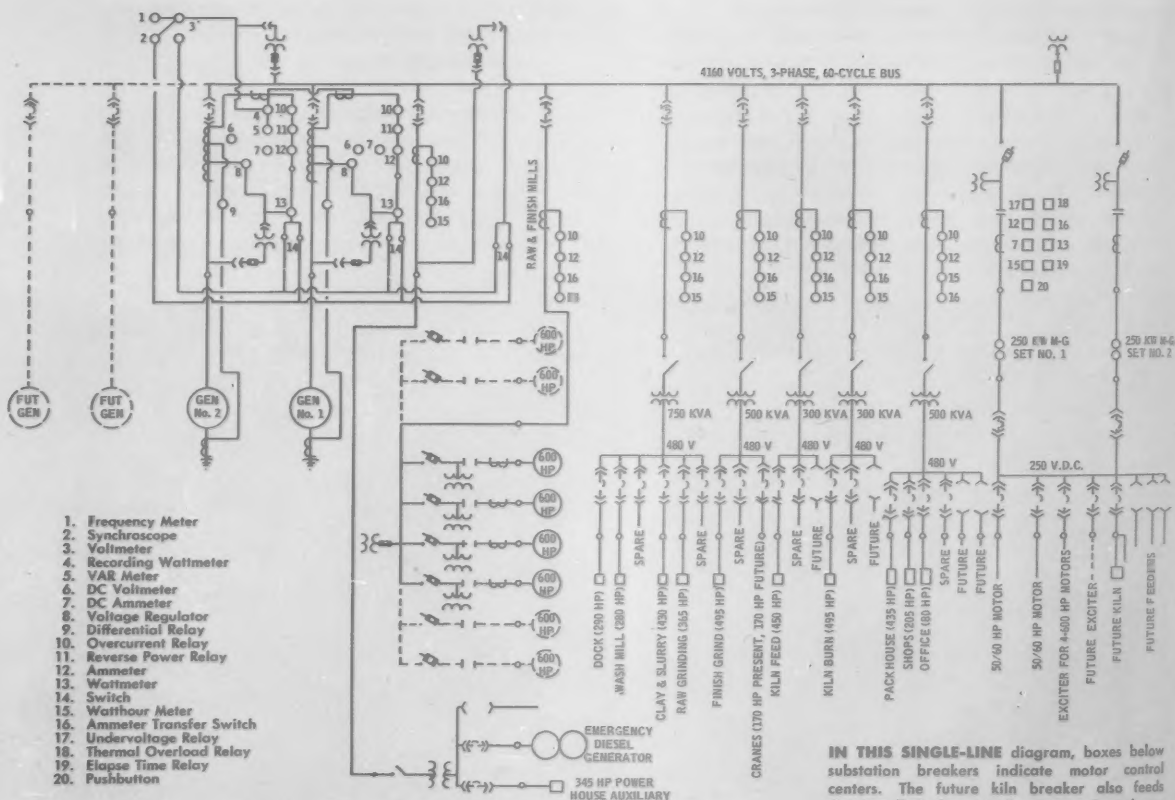
BALL MILL MOTOR STARTERS are located side by side, have variable rheostats for accurate excitation control. (FIGURE 3)

engages and disengages the clutch so that the ball mill is brought up to speed smoothly. The load relay disengages the clutch at 170 percent of motor full-load current and recloses at 130 percent of rated motor current. By applying load in this manner, the ball mill motors are started without causing objectionable voltage fluctuations on the system. The use of magnetic clutches also permits jogging without the addition of expensive accessory equipment. The four 600-hp motors driving ball mills through clutches are shown in Figure 2.

Controllers for the four 600-hp, 4160-volt ball mill synchronous motors are shown in Figure 3. Each of these controllers is an across-the-line starter. Each has an undervoltage relay, three thermal overload relays, one ammeter and ammeter transfer switch, one dc ammeter for field current, one wattmeter, one watthour meter, one elapse time integrator, and a start-stop pushbutton station. The meters give complete information on the power requirements of the motor, while the relays provide overload and undervoltage protection.

Lower voltage selected for smaller motors

An operating voltage of 480 volts was selected for the smaller motors. Both motors and control equipment is less costly at this voltage, and power requirements are small enough during starting so that voltage regulation is not a problem. This voltage was used instead of 550 be-



IN THIS SINGLE-LINE diagram, boxes below substation breakers indicate motor control centers. The future kiln breaker also feeds the installed dc control center. Powerhouse substation is rated 300 kva. (FIGURE 4)

cause it is a more established voltage and motors are more readily available.

In order to power these small motors of lower voltage, step-down transformers were necessary. Whether to locate all step-down transformers in one place or to spot them throughout the system required careful consideration of the advantages and disadvantages of each method.

First consideration was given to placing all transformers together to take advantage of the diversity factor between motors. Transformers can be paralleled so that a smaller total kva capacity is necessary. However, if all of the transformers were placed in one location and paralleled, the following disadvantages would result:

The available short circuit current on the low voltage feeders would be high, requiring 75,000-ampere interrupting capacity breakers. Long lengths of low voltage cables from the step-down station would be necessary, resulting in the use of very large cables. Circuit breakers, cable and conduit costs, as well as installation costs, would be very high.

Many of the 600 and 700-foot long runs of large size low voltage cables would carry high currents. This would result in poor voltage regulation as well as undervoltage at many of the small motors throughout the plant. In a cement plant, high starting torque is of particular importance for many motors. In addition, a motor is capable of being loaded heavier without overheating when operated at its rated voltage rather than at undervoltage.



TYPICAL of those throughout the plant, this 750-kva substation, cable connected to the adjacent motor control center, is located in the raw grinding mill area. (FIGURE 5)

Then, too, if all step-down transformers were together in the same place, control equipment to provide adequate short circuit protection would be expensive and impractical.

Branch feeder protection for the motors could be provided by less expensive breakers of 25,000-ampere interrupting capacity, with the expectation that if the equipment were damaged by higher fault currents it would be cheaper to replace the protective device. This practical solution is not desirable because of the inherent danger to operating personnel and to the equipment.

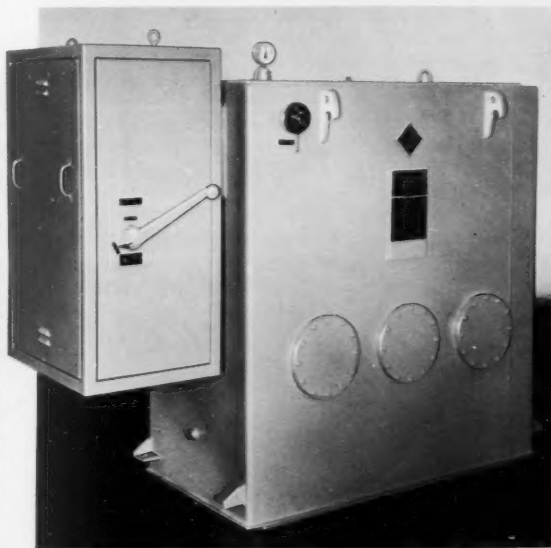
It would also be impractical or expensive to install branch feeder cables with adequate short-time current carrying capacity so that no damage would result when a fault in the cable occurred. Fault current of sufficient magnitude to damage the cable could occur at some point in the cable close to the source. This condition is undesirable and might result in costly cable replacement.

Since voltage regulation would be poor and operating voltage would drop below rated potential, motor efficiencies would be lower than at rated voltage and less load could be carried without overheating.

Central location of transformers rejected

By placing unit substations at various load centers, such as the powerhouse, raw grinding area, finish grinding area, kiln feed area, kiln burning area, and pack house, the disadvantages of locating all step-down transformers in one location are either eliminated or very much reduced. In addition, the following advantages are realized:

Transformer impedance of the unit substations will limit fault current to a value of less than 25,000 amperes. Breakers of this size are economical. Long length of large,



SEALED DRY-TYPE TRANSFORMERS were used in all load center unit substations because of their greater reliability and reduced maintenance requirements. (FIGURE 6)

low voltage cables are eliminated. Voltage regulation is good. The percent voltage drop in the 4160-volt cable is very much less than its counterpart in the other scheme.

Available short circuit current of less than 25,000 amperes permits adequate short circuit protective devices in the branch feeders to the motors. Feeder cables with adequate size to withstand this current for the time it takes the protective device to operate are practical.

Since voltage regulation is good, each motor develops torque corresponding to its rating. The motors operate at their top efficiency and are capable of carrying more load without overheating than would be possible under the other system.

For these reasons, load center unit substations were picked for this particular plant as definitely superior from both economical and operation standpoints. A single-line diagram of the distribution system is shown in Figure 4.

Load center unit substations used

The 750-kva load center unit substation installed in the raw grinding mill area is shown in Figure 5. This unit substation consists of: (a) An incoming line section having a 3-pole, 2-position disconnect switch. (b) One hermetically sealed dry-type load center unit substation transformer rated 750-kva, self-cooled, three phase, 60 cycle, 160 C rise. The high voltage winding is 4160 volts delta connected with two 2½ percent full capacity taps above and below normal; low voltage winding is 480 volts wye connected with neutral brought out and connected to the ground bus of the low voltage switchgear. (c) Low voltage metal-enclosed switchgear having one auxiliary compartment for the bus connection from the transformer to the switchgear and six air circuit breakers which are triple-pole, single-throw, 600-ampere frame size, manually operated drawout type with interrupting capacities of 25,000 amperes each. Thermal-magnetic type trip coils with one trip coil on each phase for overload and short circuit protection are used on the breakers.

Since load factor for the motors was taken into consideration when determining cable size, it is theoretically possible for all connected motors to be operating simultaneously at rated loads. In this case the current-carrying

capacity of the cable would not be adequate. Overload protection for the cables is provided by the thermal portion of the thermal-magnetic trip devices of the breakers in the low voltage portion of the unit substation.

Sealed dry-type transformers were used for this application because of their indoor location. Oil-filled transformers can be a fire hazard if located indoors. Therefore, there was the choice of using *Chlorextol* liquid-filled transformers or dry-type transformers. Periodic filtering of *Chlorextol* liquid is necessary, and its handling requires a certain amount of knowledge and technique. The conventional open ventilated dry-type transformer requires special care to keep the coils clean; even then, air duct size and insulation clearances probably would be reduced in time, making the transformer susceptible to overheating and coil failures.

Sealed dry-type transformer has advantages

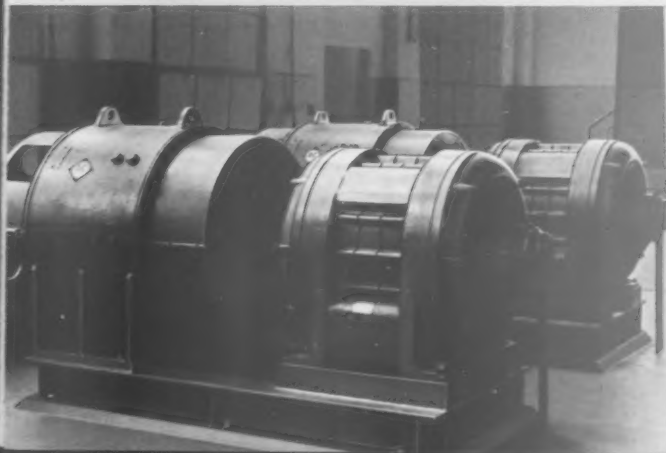
The sealed dry-type transformer eliminates disadvantages of the *Chlorextol* liquid-filled transformer, the oil-filled transformer, and the open dry-type transformer. The core and coil assembly of a sealed dry-type transformer is enclosed in a sealed tank filled with nitrogen. It is not susceptible to dust, foreign matter, or moisture. Therefore, maintenance is reduced to a bare minimum by using sealed dry-type transformers, one of which is shown in Figure 6.

While sealed dry-type transformers cost more than other types, the additional expenditure is small when compared to the overall cost of the entire plant. The increased price would probably be justified solely from the standpoint of greater reliability. Reliability was an important consideration, since this installation is remote from the supply source of spare parts and replacement units. In addition to this, the decreased cost of maintenance should offset the higher original equipment cost.

Selecting motor feeders

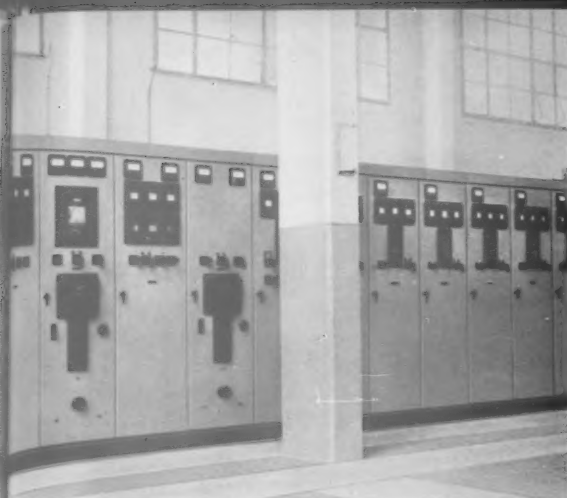
Next, a method of feeding power from the unit substation to the various low voltage motors had to be selected. A feeder from the unit substation could be used to feed a number of separately mounted combination motor starters directly, or distribution panel boards could be placed between the substation and the motor starters.

SUPPLYING DIRECT CURRENT for the entire plant, these 250-kw generators are driven by 300-hp, 4160-volt motors. (FIGURE 7)



VARIABLE SPEED for each of the two kilns is provided by a 50/60-hp dc drive motor through a gear reducer. (FIGURE 8)





ALL LOAD CENTER unit substations are fed from this 4160-volt switchgear, which also contains generator control equipment. (FIGURE 9)



ALL DC EQUIPMENT is powered through this switchgear placed adjacent to the ac switchgear shown in Figure 9. (FIGURE 10)

Motor control centers were selected using Type C construction, with all power terminals and secondary control cables brought to terminal boards. Connections for proper interlocking were easy to make. In a cement plant, considerable interlocking between controllers is necessary so that continuous processes will not be unduly interrupted. For example, if the last motor in the continuous process stops, all other motors in that process should stop. If the first motor in the continuous process stops, there would be no need for the motors after it to stop. Because of this requirement, provision was made for interlocking between each and every controller.

While equipment cost of control centers is probably greater than for the alternate arrangement, installation time is shortened, cost of cable, conduit, and wiring is reduced. These factors, together with savings of time and effort in coordinating components, resulted in motor control centers being very competitive in price.

Motor control centers permit the installation of all control in one place which can be kept reasonably clean and accessible. In this way operation and maintenance is simplified, and a neat appearing installation achieved. The motor control center behind the unit substation in Figure 5 is typical of those used in this installation.

Direct current distribution equipment

In a cement plant, dc power is necessary for variable speed motors and for field excitation of synchronous motors. Since only resistance is involved in cables for dc systems, voltage regulation does not present a problem. The amount of power required for dc is not large. Therefore, all of the dc generating equipment could be placed in one location.

For this particular project two motor-generator sets, each having a 250-kw generator driven by a 300-hp, 4160-volt motor, were installed—one unit to serve as a standby unit. In this case 4160-volt motors were selected because 480-volt motors would have required additional step-down transformer capacity. This additional capacity would have been more costly than the price differential for the higher

voltage motor winding. Figure 7 shows these 250-kw motor-generator sets.

Each motor-generator set is cable connected to a generator breaker in the 250-volt metal-enclosed switchgear. This switchgear supplies dc power to the four 600-hp synchronous motors, the two 300-hp synchronous motors for the motor-generator sets, the two 50/60-hp variable speed kiln motors shown in Figure 8, and the dc motor control center which supplies power to various other variable speed dc motors.

Alternating current distribution equipment

The ac distribution system consists of the main switchgear containing six 4160-volt breakers feeding six 480-volt ac motor control centers. This type of distribution resulted after considering the following factors:

The centers of load generally fall in the area of a certain department, and the motors in that area are chiefly those for that department. This unit type of layout lends itself to efficient operation and maintenance.

Each department operates to a great extent independently of the others and, therefore, its power supply should be as completely independent as is economically feasible. The accounting procedure of this plant, like that of most cement plants, requires separate cost records for each department. With this system, power consumption is recorded by a watthour meter on the front panel of each 4160-volt circuit breaker feeder unit, and the power consumed by each department is easily determined.

In most instances it would not be economical to use a larger size unit substation serving greater areas because of the increased length of low voltage feeder cables, resulting in greater cost of low voltage cable, poorer voltage regulation, lower efficiency, and less desirable motor torques.

The lineup of 4160-volt metal-clad switchgear is shown in Figure 9. Two 300-hp motor starters, only partially shown, are located to the right of this lineup. The first and third cubicles from the left are for the two 1875-kva generator units. Cubicles 2 and 4 contain field application and associated equipment for each of the generators.

Cubicle 5 feeds power to the load center unit substation, which in turn supplies power to the powerhouse auxiliaries. Number 6 is a feeder for the 4160-volt control lineup which supplies power to the four 600-hp ball mill motors. Units 7, 8, 9, 10, and 11 are feeder breakers, one for each of five load center unit substations which are located in the raw grinding area, finish grinding area, kiln feed area, kiln burning area and pack house area, respectively.

The last two units are for the 4160-volt motor controllers for the two 300-hp synchronous motors. The same complement of relays and meters are included as for the 600-hp motor controllers shown in Figure 3. Figure 10 shows the second of these two controllers and the 250-volt dc metal-enclosed switchgear.

Lighting distribution system

A 25-kva, three-phase transformer was located near each motor control center to power the plant lighting equipment. This arrangement was selected because of its operational characteristics and because the transformers were low in cost and economical to protect.

Light flicker caused by the starting of motors powered through the same control center is not objectionable for several reasons: First, the motors are relatively small in size, and frequent starting is not an operational requirement. Then, too, stepping voltage down from 4160 to 480 with unit substations located adjacent to the load centers resulted in excellent voltage regulation. In addition, it is satisfactory from an operational standpoint to have power for lighting only when the main bus of the motor control center is energized.

An added feature of each motor control center is a welder receptacle to facilitate the use of portable welders for maintenance operations.

Emergency power system

An emergency power source is required for this cement plant for the following reasons:

(a) For operating the power plant auxiliaries after the 1875-kva generators have both been shut down and before the generators are again put into operation.

(b) To provide emergency power for motors turning the kilns, since a kiln will be damaged unless it is kept turning while hot.

(c) To provide emergency power for lighting and to provide a limited amount of power for maintenance and repair purposes. The 175-kw diesel generator is cable connected to the switchgear of the load center unit substation feeding the powerhouse auxiliaries. By using the 300-kva transformer of the load center unit substation shown on Figure 11 as a step-up transformer, it is possible to obtain 4160 volts from this unit and feed a limited amount of power to any other portion of the distribution system.

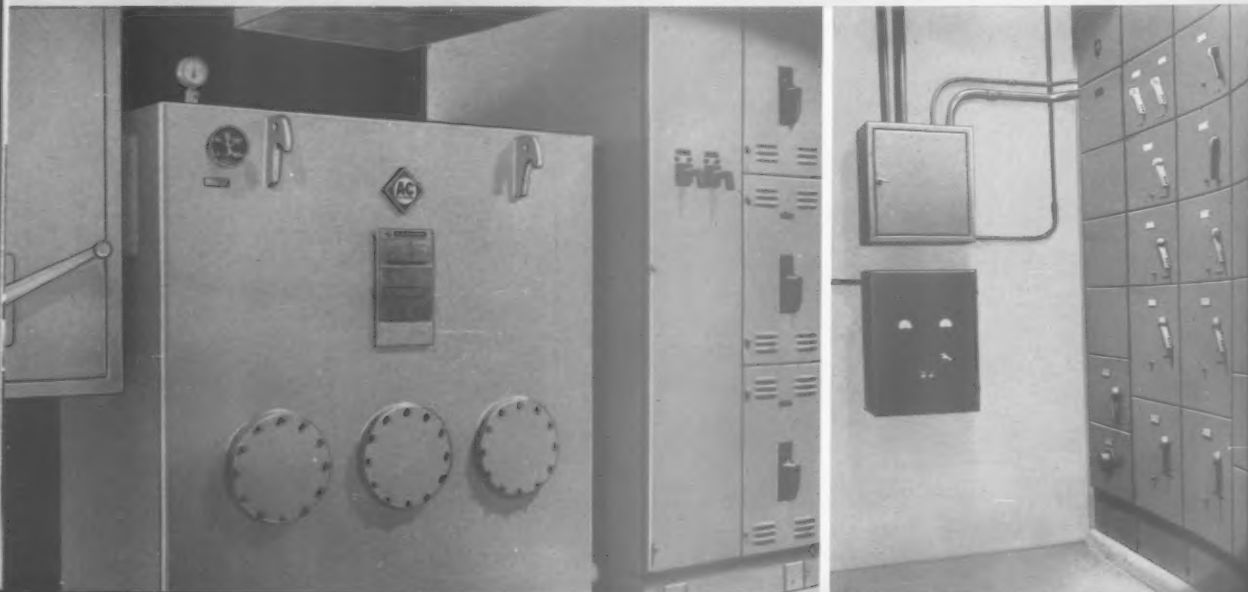
The motor control center shown in Figure 12 is fed from the 300-kva unit substation, and supplies power to the motors of the powerhouse auxiliaries.

Provision was made for paralleling the 175-kw generator with the 1875-kva generators so that the powerhouse auxiliaries will not have to be dropped while transferring the load from the emergency power unit to the main power source. To facilitate this, the breakers in the low voltage switchgear of the powerhouse unit substation are controlled from a panel in the 4160-volt metal-clad switchgear.

When building and equipping a new plant such as this one, economic considerations as well as service requirements influence sound engineering practice. Both of these factors were considered in selecting the electrical equipment for every part of this new and modern cement plant.

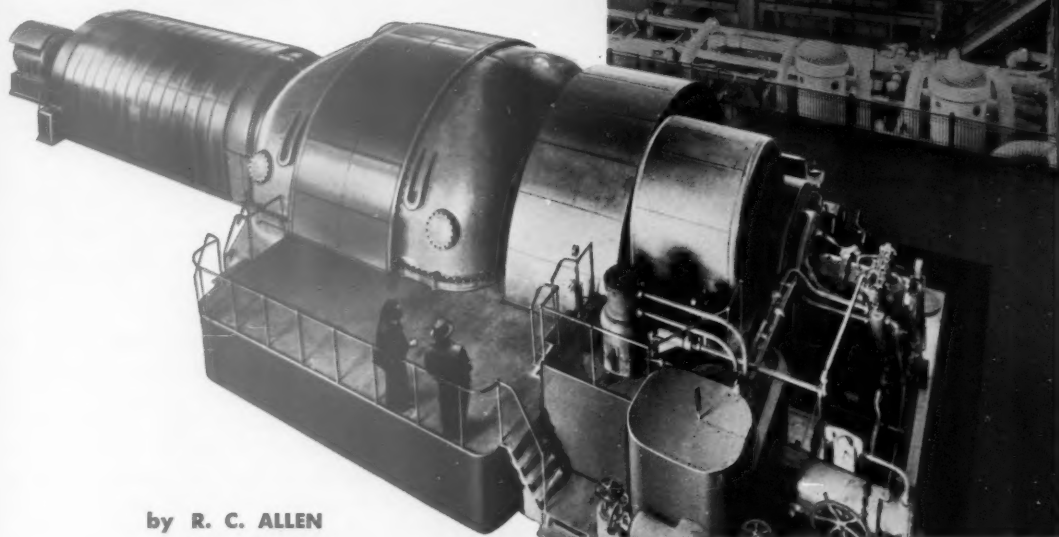
DOING DOUBLE DUTY, this 300-kva substation not only steps down 4160 to 480 volts for powerhouse auxiliaries, but also steps up emergency power from 480 to 4160 volts. (FIGURE 11)

POWERHOUSE AUXILIARIES are supplied through this motor control center, typical in design and appearance of all motor control centers used in this modern cement plant. (FIGURE 12)



Steam Turbine HISTORY HIGHLIGHTS

PART II



by **R. C. ALLEN**

Consultant Engineer
Allis-Chalmers Mfg. Co.

RATINGS ENVISIONED as early as 1918 resulted in Waukegan 1800-rpm 25,000-kw, 35,000-kw, 50,000-kw, 65,000-kw reheat and the 115,000-kw reheat (foreground) units built between 1923 and 1931.

This, the second in a series of three articles, gives steam turbine history during the early part of this century.

IN ABOUT 1900 the practical phase of steam turbine design began in earnest. Before this time steam turbine construction was based on limited theory and research in fluid flow engineering. Turbine designs prior to that time were influenced mostly by manufacturing considerations and indicate that inventors did not fully recognize the necessity of minimizing shock losses in steam flow at each bladed element entry. Nor did they recognize the need of adopting passage contours which would permit the flow of steam through the blade passages with the least frictional and eddy losses. It is significant that the individuals who achieved distinction as successful commercial steam turbine developers, particularly Parsons, DeLaval, Rateau and Curtis, recognized the general nature of steam flow requirements. They adopted mechanical constructions which permitted the use of blade and nozzle passages with efficient fluid flow forms.

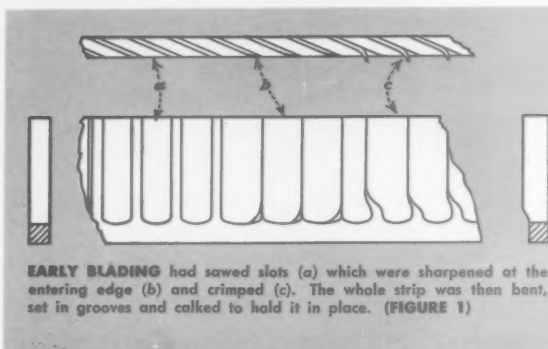
Figure 1 illustrates the form of blade path resulting

from consideration of convenient manufacturing processes. Test results with these blades quickly led to the development of the crescent-shaped reaction blade section shown in Figure 2.

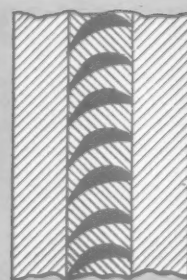
Patent records show that many inventors, due to lack of theoretical knowledge, proposed blade shapes in which the main objectives appear to be maximum reduction of kinetic energy in the rotating element by setting up eddy and friction losses. Others proposed blade forms which were extremely costly to manufacture. With the adoption of efficient low cost blade and nozzle forms, steam turbines soon became established commercially.

Crescent-section blades and spacer pieces which could be produced in bar lengths by rolling or drawing were among some of the first successful attempts at practical turbine construction. Individual blades and spacers were then cut off and secured in the moving and stationary elements. Other builders developed means for machining the blades as an integral part of a metal segment. This segment was then bolted to the side of the main turbine wheel.

The forms of blade roots and method of fastening were found to strongly influence cost. The following four types



EARLY BLADING had sawed slots (a) which were sharpened at the entering edge (b) and crimped (c). The whole strip was then bent, set in grooves and calked to hold it in place. (FIGURE 1)



PARSONS used crescent blading in 1894. (FIGURE 2)

of fastenings had been reduced to practice by the turn of the century.

1. Drawn blade and spacer sections cut off to required lengths and having dovetail or serrated roots for assembly in matching grooves in the wheel.

2. Pin-type fastening in which the root of the blade was formed with one or more tongues that entered grooves in the periphery of a disk, with transverse pins to hold the blades in place.

3. Blades having an integral base section which entered a similarly formed circumferential T-slot groove in the periphery of the spindle or disk.

4. Blades having integral roots with transverse key sections which fitted into corresponding transverse grooves in the rim of the wheel.

Ingenious casings developed

Casing design received much attention, particularly with regard to means for the reduction of thermal distortion. Some of the early casings were masterpieces of foundry practice. Figure 3 shows the section of a turbine built in England in 1896. The integral steam balancing passages in the top of the casing were the cause of thermal distortion difficulties and were later abandoned. The use of external bracing ribs was also abandoned for similar reasons.

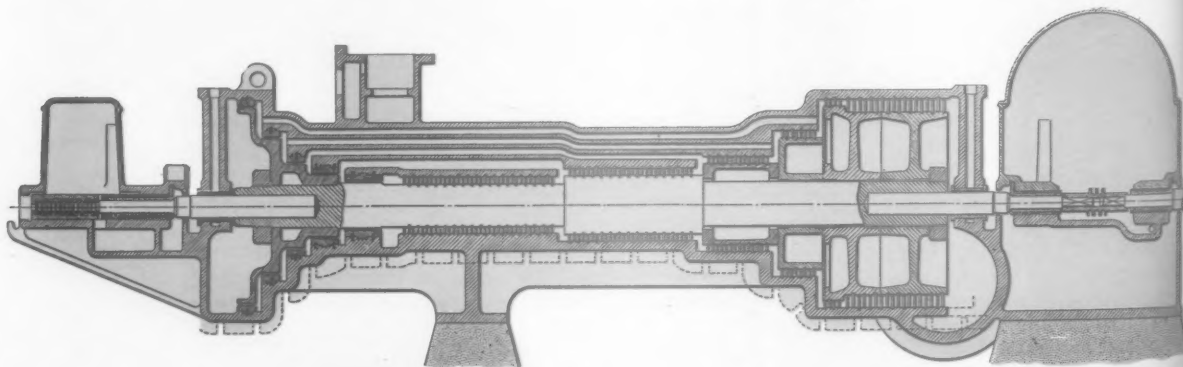
Since steam temperatures had not yet advanced to the level where the rate of growth of cast iron became objectionable, substantially all of the early turbines were constructed with cast iron casings. The common operating condition for electric power generating plants was 150 psig, dry and saturated steam.

Another interesting practice included the building of reaction turbine spindle, components from steel castings. Although sound structures were achieved, the physical properties of the cast materials were too low for commercial turbines of later design periods.

Figure 4 shows how steel spindles were cast. The axis was vertical and coincident with the axis of the ingot. The contour of the shaft end casting usually had an included cone angle not exceeding 90 degrees. As a result the steel, in the process of solidification, had little resistance against sliding down to fill the cavities which might otherwise be caused as the ingot cooled. Turbines totaling several millions of kilowatts were built with cast steel spindles.

Governors received much attention

Because of the run-away hazards of high speed machinery, the governing of steam turbines seriously concerned development engineers from the start. The first governors were the direct mechanical type in which the governing forces were derived from the centrifugal forces of rotating



DISTORTION caused the abandonment of intricately cast cylinders. (FIGURE 3)

weights. These weights were usually opposed by a spring of appropriate scale. The governors were satisfactory where dimensions of the governor head could be large in relation to the size of the steam valve.

It became apparent in the operation of some of the first turbines that, in order to obtain acceptably precise and fast regulation, a relay mechanism should be developed whereby the small forces available from the governor itself could control a sensitively balanced pilot valve. The pilot valve would, in turn, regulate the positions of the main control valves through the use of an intermediate control fluid, such as air, steam, or oil. An early governor with an oil relay control mechanism is shown in Figure 5.

The governor on the first Parsons steam turbine, shown in Figure 5, Part I of this article, was a combination vacuum and electrical governor, as follows:

1. A centrifugal impeller mounted on the turbine shaft served to produce a partial vacuum in a vertical standpipe, which provided a head of oil above the centerline of the turbine shaft and supplied oil to the suction of the lubricating oil pump on the main shaft.

2. The partial vacuum also acted on a leather diaphragm to which was connected a lever operating a rotating piston steam valve. Variations in speed changed the negative pressure on the diaphragm which, in turn, regulated the steam valve as required by load change.

3. A rotary air valve was located on top of the generator field magnet and was operated by the stray magnetic field. The rotation of a soft iron bar about a vertical axis opened or closed the air valve connected to the vacuum line. This device modified the shaft speed at which the main governing valve opened or closed. This valve is shown in Figure 6.

"Gust" governing, first employed on turbines by Parsons, included the relay feature already described, and used high

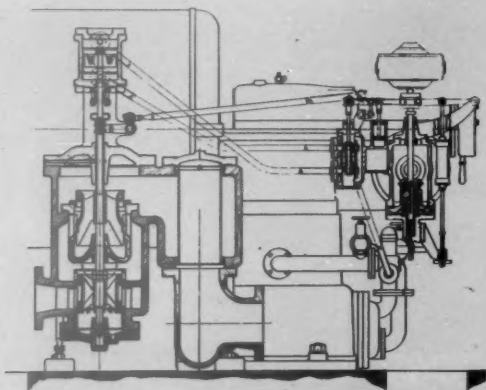
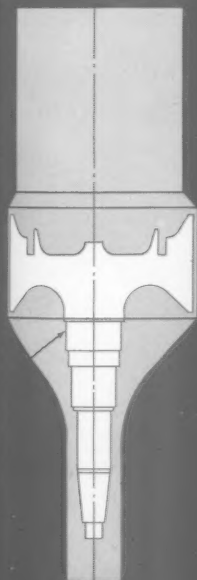
pressure steam as the motive control fluid. The connecting pipe from the pilot valve port led to the underside of a steam piston which was held in the down position by a spring. This steam piston was mounted directly on the control valve stem. An eccentric, driven from the main shaft, imparted a reciprocating motion to the pilot valve sufficient to cause a continuous oscillation of the main control valves. This method of governing contributed to the precise control of large turbines by minimizing friction.

Bearings developed

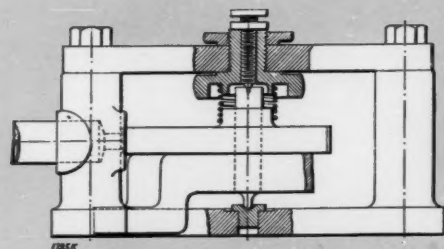
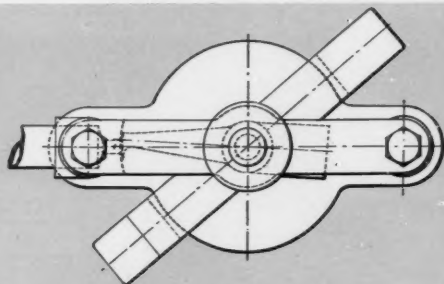
Steam turbine engineering requirements greatly accelerated the development of fluid film bearings. The early turbine engineers did not hesitate to run their machines at rotative speeds up to 30,000 rpm. Limited knowledge of critical speed phenomena and balancing resulted in considerable vibration trouble, particularly at these high speeds. These troubles were solved by several designers through the use of flexibly mounted bearings.

The Parsons flexible tube bearing, shown in Figure 7, consisted of a non-split babbitt-lined inner tube which was the bearing proper. Surrounding this inner tube was a series of thin concentric tubes with a clearance of a few thousandths of an inch between. The outermost tube was rigidly mounted in the turbine pedestal. Lubricating oil was permitted access to the capillary clearances between the tubes. The tendency to vibrate accelerated the feeding of oil into the capillary spaces so that the inner bearing tube was effectively supported on a hydraulic cushion which contributed flexibility and damping under conditions of shaft vibration. Many turbines with the Parsons oil tube type bearing are still in use.

As the nature of critical speeds and vibration phenomena became better understood from theoretical and practical bases, the flexibly mounted bearings were superseded by the relatively rigid bearing mounting used today.

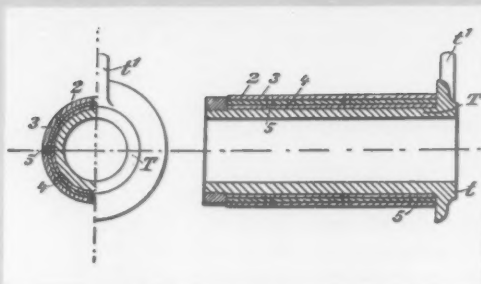


OIL RELAY type control assembly is shown with Hartung governor mounted at top right. (FIGURE 5)

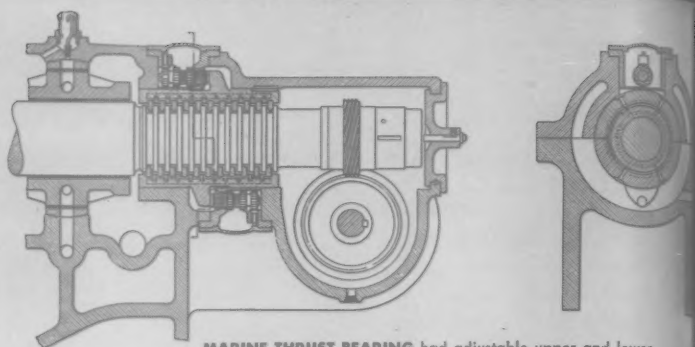


MAGNETICALLY CONTROLLED modulating air valve was used with Parsons' first turbine governor. (FIG. 6)

QUALITY STEEL spindle castings had heavy top section where shrinkage cavities formed and into which impurities rose. (FIG. 4)



FLEXIBLE TUBE journal bearing consisted of bearing (1), outer tubes (2) (3) (4) and oil access holes (5). (FIGURE 7)



MARINE THRUST BEARING had adjustable upper and lower thrust blocks. To prevent tampering, adjustment mechanism was deliberately made inaccessible. (FIGURE 8)

Due to the close axial running clearances the axial location of turbine spindles is very important. Many of the early turbines were built with a flat thrust collar at each side of one of the main turbine bearings. It was found that the steam unbalance of multi-stage turbines was not always easy to predict and that the load-taking capacity of a flat collar was not very great. These experiences led to the adoption of a multiple collar marine-type thrust bearing such as shown in Figure 8.

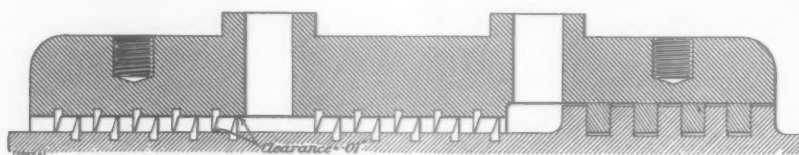
One reaction turbine builder developed a technique whereby the end thrust of the turbine could be approximately gauged by the forces required to move the adjusting screws of the upper and lower halves of the thrust bearing. When the turbine was in operation and under load, it was customary to move the spindle a small amount and judge the condition of axial unbalance by the relative effort applied to the adjusting screws. If the unbalanced end thrust did not come within the established limits, it was

customary to take the turbine apart and twist or "gauge" the reaction blades.

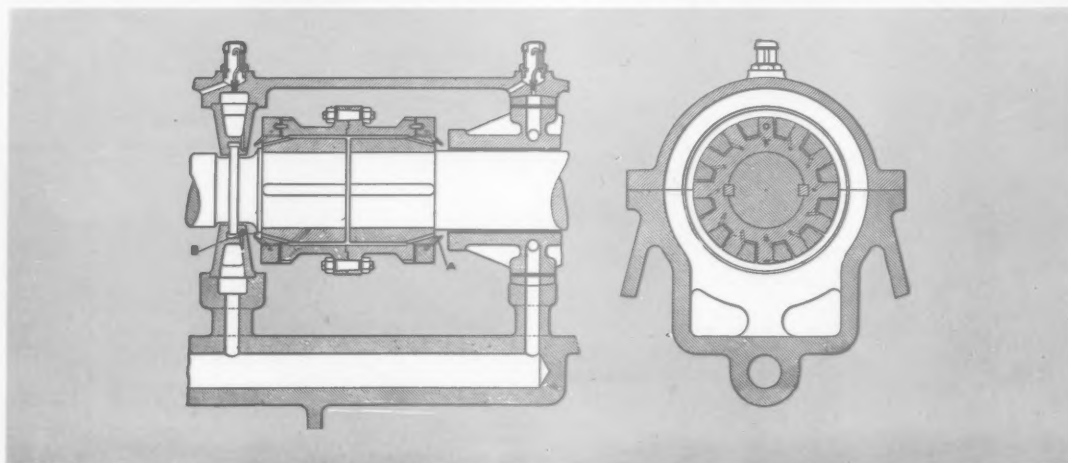
Shaft seals improved

A troublesome detail in the construction of the first steam turbines was the sealing at each end of the casing. Parsons recognized in his earliest machines that shaft seals must be so designed that in the event of an accidental rub, the amount of heat generated would not be sufficient to cause appreciable damage. In his solution, thin-edged seal strips of a nonferrous alloy were arranged to run with close tolerances. An accidental rub was found to wear the strip material without serious damage to the shaft. Figure 9 shows a typical gland of this type.

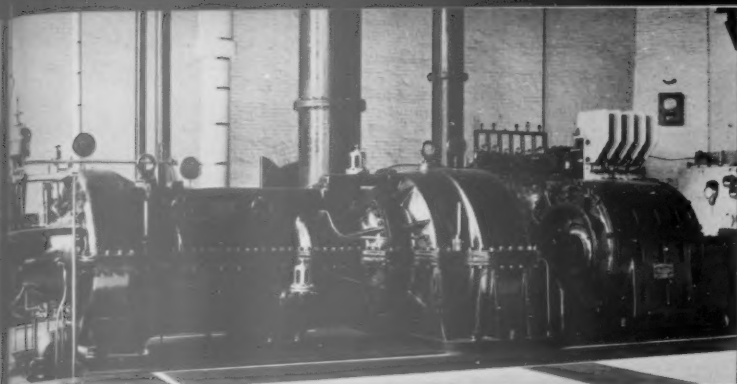
As pressures and temperatures increased, yellow brass seal strips became unsuitable. Hence, alloys were employed which have much less favorable wear and heat generating characteristics during an accidental rub. These effects have been mitigated by employing spring-mounted



SEAL STRIPS AND PISTON RINGS used in early marine turbines. (FIGURE 9)



CLAW TYPE FLEXIBLE COUPLING of 1910 provided for axial spindle adjustment and shaft expansion. Oil entered at A and B. (FIGURE 10)

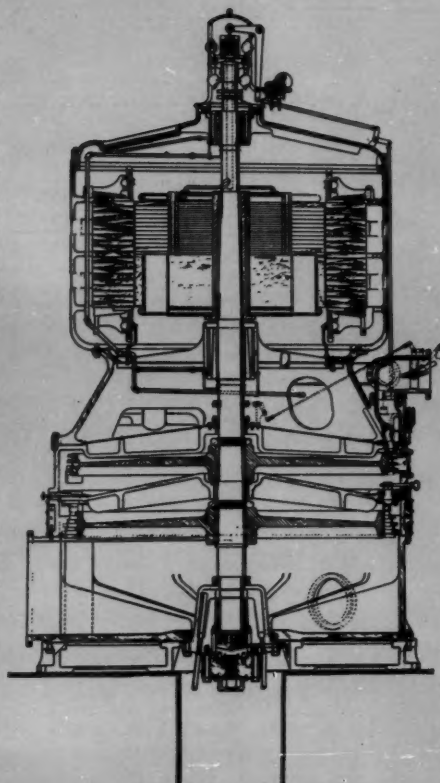


VALUABLE DESIGN DATA was gained in the eight years this unit was operated at Hartford Electric Light Company. (FIGURE 11)



FIRST TANDEM TURBINE doubled the capacity of that time. This Elberfeld unit established Parsons on the Continent. (FIGURE 12)

HIGH PRESSURE OIL supported the shaft weight of pioneer vertical turbine installed at Fisk Station in 1903. (FIGURE 13)



groups of strips to reduce the forces which might otherwise be generated with accidental contact.

Figure 9 also shows a piston ring type of gland used in some of the earliest machines where the steam in the outer seal space contained considerable moisture, and under conditions where the pressure drop was small and the speed of the contact surfaces was low.

Many steam turbines have been built with water seals in which an impeller supplied with condensate establishes a ring of water under centrifugal pressure. The radial depth is such that the centrifugal head difference between the two sides of the impeller is somewhat greater than the difference between the casing pressure and the atmosphere. When surface speeds were low and operating steam temperatures were moderate, these glands gave excellent service. With increased temperatures, excessive cooling of the shaft by the water seal proved objectionable. With larger diameters at high speed, the power losses increased, substantially. These considerations brought about a return to the steam-sealed gland. An early patent which refers to a centrifugal-type water seal for a rotating shaft was granted to E. C. Terry in 1899.

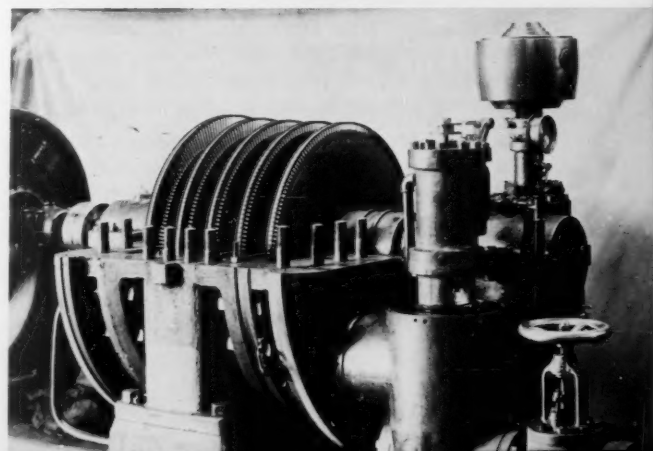
The so-called flexible coupling came into the picture around 1900. Some of the earliest of these couplings consisted of a sleeve with a square hole that fitted over the squared ends of the turbine and generator shafts.

There were small clearances in these squared fits. The main purpose of a flexible coupling was to break up a long shaft into two or more components and to permit some amount of accidental misalignment. In later designs the driving members were formed by a series of interlocking claws as shown in Figure 10.

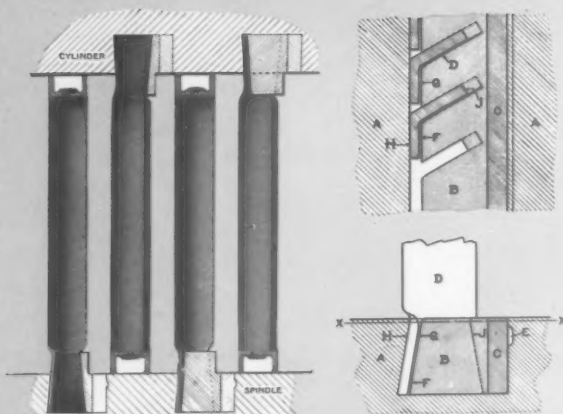
Recent years have seen the abandonment of the flexible coupling and the adoption of solidly bolted main couplings in large turbine units.

Hartford-Elberfeld

At the turn of the century the largest steam turbine in operation was the 1500-kw unit installed in the Pearl



PATITZ IMPULSE TURBINE rated 25 kw at 2400 rpm was built as test model in 1910. (FIGURE 14)



BLADING SYSTEM invented by Capt. Riall Sankey, managing director for Willans & Robinson, Rugby, England. (FIG. 15)

*Brooklyn Edison Co.
5000 Kw turbine unit - complete
except condenser \$90,000
30 day option on it more at same price
date 7/11/1904
our 1500 Kw. unit for Utica (delivered
and in operation Dec 1) complete
Jat-Condenser price \$35,000
Thos E Murray*

PERSONAL ORDER penciled by Thomas E. Murray in 1904. (FIGURE 16)

Street Station of the Hartford Electric Light Company in Hartford, Connecticut, shown in Figure 11. This 1200-rpm turbine operated with an inlet pressure of 155 psig and a superheat of 40 F. The vacuum was approximately 27 inches of mercury. The steam rate was reported to be 19.1 lb per kw-hr and the engine efficiency 58.2 percent.

At about the same time, Parsons installed two 1000-kw tandem-compound steam turbine generating units at Elberfeld, Germany. The steam consumption reported on these machines was 19.0 lb per kw-hr. The Elberfeld installation is shown in Figure 12. The installations at Hartford and Elberfeld represented the high-water mark of steam turbine construction in 1900.

U. S. large turbine builders get start

In 1895, the work of Sir Charles Parsons in the commercial development of steam turbines attracted the attention of George Westinghouse, who negotiated a license agreement for the manufacture of such turbines in the United States. In 1896, Francis Hodgkinson was transferred from the Parsons staff in England to supervise the development by Westinghouse of the Parsons turbine in this country.

The General Electric Company entered into an agreement with Charles G. Curtis, the inventor of the Curtis turbine, in 1897, for the manufacture and exploitation of this prime mover. W. L. R. Emmet was assigned to the Curtis development in 1901.

A notable early installation was the 5000-kw vertical turbine installed at the Fisk Station of the Commonwealth Edison Company in 1903. This is a two-pressure stage turbine with a 4-row velocity-compounded wheel in each stage. The sectional drawing is shown in Figure 13.

In 1899, Max Patitz, consulting engineer of The Edward P. Allis Company, called the attention of Edwin Reynolds to the steam turbine, pointing out that this prime mover could be expected to be a serious competitor of the reciprocating steam engine which was then a major line of Allis apparatus. Reynolds was interested in this development, although definite steps were not undertaken

toward its exploitation until the formation of the Allis-Chalmers Company in 1901.

Several types of steam turbines were built and tested, including a 6-stage low velocity ratio impulse unit arranged for the operation of each stage with means for utilizing the high carry-over. Figure 14 shows a 25-kw multi-stage impulse turbine designed similar to that developed by Patitz in 1904.

License agreements were negotiated by Allis-Chalmers to employ the Sankey system of blading, shown in Figure 15. An agreement was consummated in 1905 with C. A. Parsons & Company to build reaction turbines.

Thomas E. Murray purchased a number of machines from Allis-Chalmers in 1904. The first of these, shown in Figure 6, Part I, was assigned to the Utica Gas & Electric Company and installed by A. G. Christie in 1905.

The next turbine of this group was a 5500-kw unit which was installed in the Kent Avenue Station in Brooklyn. Figure 7 of Part I shows this unit, which was designed and built in the Allis-Chalmers Milwaukee shops.

Figure 16 shows an interesting sidelight on the early turbine developments in the form of a longhand order by Thomas E. Murray for the construction by Allis-Chalmers of two large steam turbines.

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- "The Steam Turbine in the United States," A. G. Christie, *Mechanical Engineering* (Part II, February, 1937), pp. 71-82.
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Allis-Chalmers Electrical Review • Third Quarter, 1953

600-KV TRANSFORMER

Establishes New Insulation Levels

MORE THAN EIGHT YEARS OF STUDY, design, and testing have gone into building the 600,000-volt power transformer shown on the next page. It represents, in many ways, a milestone in the design of high voltage power transformers. The fact that such an extremely high voltage assembly could be built for practical outdoor power transmission service makes the story of this development an interesting chapter in electrical equipment progress.

The story began with a small-scale development project started in 1941. At that time it became apparent to transformer design engineers that the traditional "building block" method of designing bigger transformers was in need of closer study. Extrapolating insulation and conductor dimensions and spacings from smaller transformers seemed wasteful. Impulse testing, introduced a decade before, was assurance against *too little* insulation in a transformer. But whether *too much* insulation, copper and iron were being used, and whether they were properly distributed throughout the transformer assembly, was still a big question.

To learn the answers, basic assemblies of conductors, insulation, and shielding were built. Hundreds of combinations and shapes of these components were carefully constructed. Definite safe-working and breakdown levels were determined for each assembly through low frequency and impulse tests.

Test began in 1941

Work on the project was just under way when it had to be put aside in favor of urgent war jobs. Not until 1946 were transformer designers able to return to the problem in earnest. Then, as they gained knowledge, the things they learned helped improve production transformers.

Although the specific purposes of the lengthy test program were a more sound design procedure for power transformers and the elimination of corona at maximum test voltage, two significant facts became apparent in the course of the tests.

First, if low frequency test levels could be dropped, present impulse levels could be retained and transformer cost reduced without any sacrifice in performance.

Second, the practicality of this design procedure as well as its limitations, if any, could be determined by building an extra high voltage (EHV) transformer for use with lightning arrester protection.

To test this design procedure, the decision was made to build a transformer for operation on a 600-kv line-to-line transmission system. While this voltage is well beyond any level being considered today, it is within the range of practicality. And because field experience in the EHV range tends to show that standard impulse levels have been higher than necessary, the more realistic and economical values of 1850-kv chopped-wave and 1600-kv full-wave impulse tests, and 700-kv low frequency test were selected. Greater economy could have been realized by reducing the low frequency test level even more than the proportion by which the surge tests were reduced. This was not done because the project was pointed toward EHV construction experience rather than toward proving or disproving the adequacy of present standards.

Construction posed new problems

Building a 600-kv transformer called for a great deal of study and ingenuity. If the unit was to be of value for eventual test use it had to be short and compact, since it would occupy some of the most valuable floor space in the plant. To conserve space the core was clamped by the two halves of the tank shell, and the laminations and coils were placed on edge. The coils themselves were clamped rigidly after final assembly in the tank.

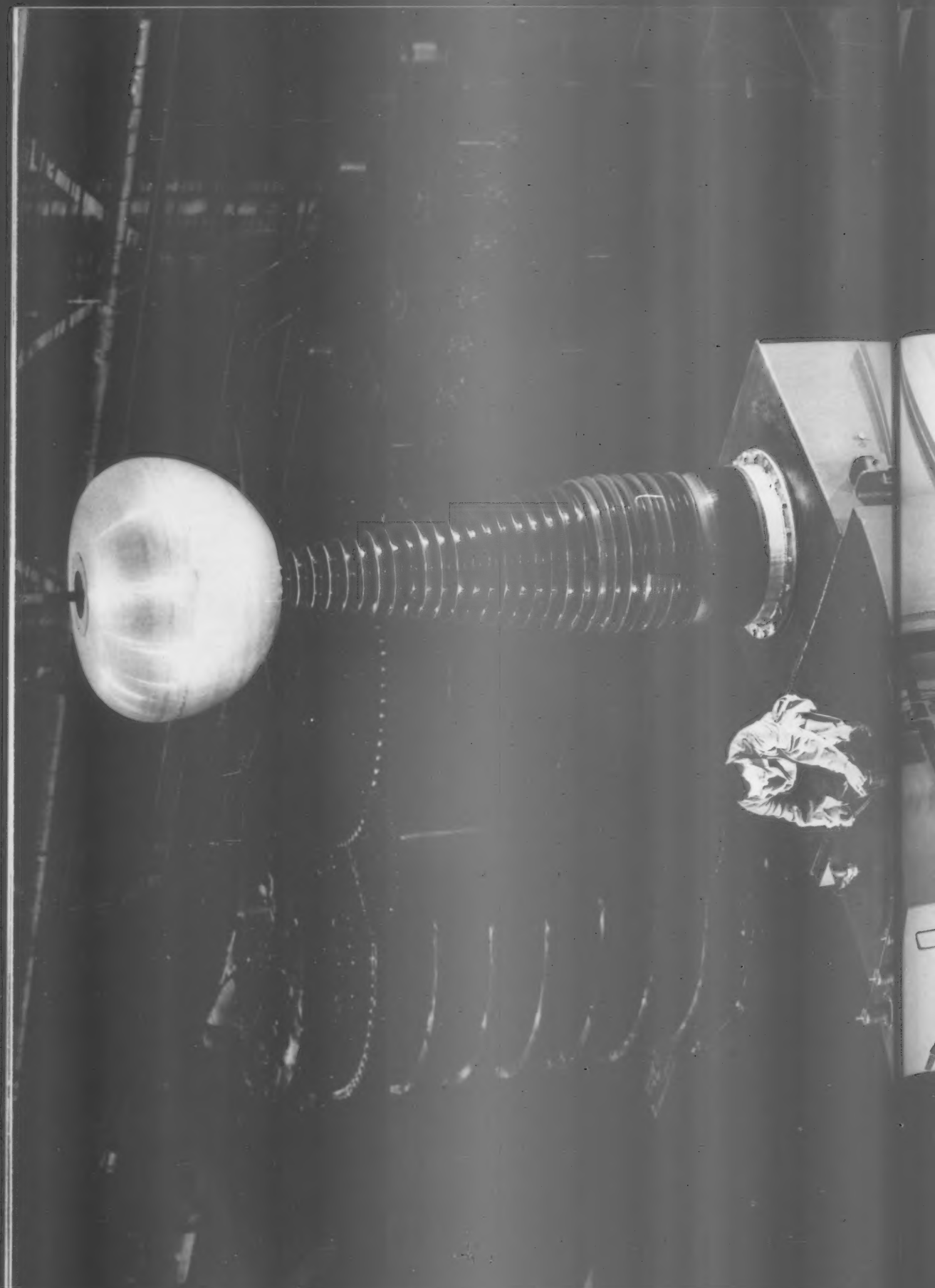
No terminal bushing for this high voltage was available, so a standard 287-kv porcelain shell was used to house the specially designed internal insulation structure. Because the tank-to-bushing terminal distance was only 100 inches, a 48-inch diameter corona cap was built to prevent flash-over during surge testing.

After assembly, the unit was tested at the design levels and then taken on up to breakdown to determine the margin between test and actual breakdown levels. This study in transformer design has clearly shown that even the most complex high voltage insulation structures used in transformers can be more efficiently designed from fundamental data than by extrapolating curves based on lower voltage insulation assemblies.

Now rebuilt, this transformer will be used to test future EHV power transformers. With commercial lightning arresters now available, this transformer could be operated on a 600-kv transmission line with adequate margins of safety.

THIS NEW 600-KV TRANSFORMER, as it appeared on the impulse test floor, is shown on the next pages.

A-C Staff Photo by M. Durante







Control of HYDRO POWER 1953

by **JOHN BAUDE**
and **T. F. FINLEY**
Switchgear Department
Allis-Chalmers Mfg. Co.

Greatly simplified, today's automatic hydro station control is making practical the use of the more remote power sites.

IMPROVEMENTS IN CONTROL COMPONENTS and overall simplification of switchgear in the last few years have made possible more effective use of water power in remote areas. Where ten years ago completely automatic stations were unheard of, today, when the erection or modernization of a remote hydroelectric station is being considered, an automatic station is almost always first choice.

Automatic control has made many marginal sites well worth considering. The expense of maintaining constant supervision by specially trained technicians in remote hydro stations can now be eliminated. Only occasional checks on the condition of the equipment are necessary. Emergencies are automatically taken care of by reliable, fast acting control.

These controls seemed at first to be complicated and very special, but when the job is divided into functions and components, it can be simplified almost to the point of standardization.

Fewer devices are actually needed than might be expected. For example, the art of building and applying protective relay equipment has advanced to a point where comparatively few relay types are needed for adequate protection and for full or partial automatic operation. The usual bulk of direct reading indicating meters has been gradually reduced, since these meters are employed only if continuous indication is needed. Switchboard panel space and cost have been greatly reduced by the use of plug-in meters where only occasional checks on circuit conditions are needed. Meter sizes today are generally smaller than



ONLY NECESSARY RELAYS, meters and devices are used on the modern hydro station control boards. (FIGURE 1)

Allis-Chalmers Electrical Review • Third Quarter, 1953

in the past. However, size is usually determined by the importance of the quantity indicated and distance at which the meter is viewed.

Mechanical features are simplified

The practice of combining power switchgear protective relays, indicating meters, recording equipment and control apparatus in one structure provides a considerable saving in overall space. This saving is made possible by fully utilizing the panel space in the switchgear units.

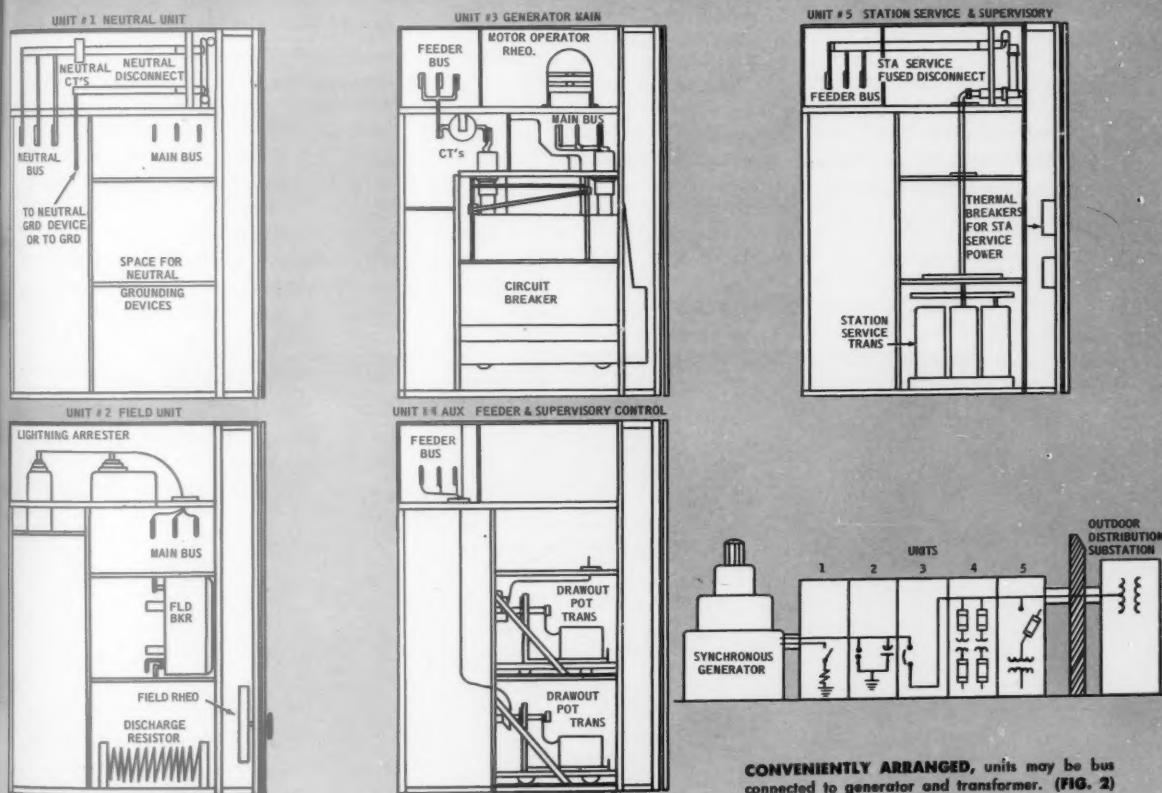
Vertical lift or other types of drawout power switchgear is especially suitable as a basic design for modern automatic hydroelectric control equipment. This arrangement is illustrated in Figure 1. The complete power switchgear and control board for two hydroelectric generators, station power and supervisory control shown are ready for installation and connection to the control battery, supervisory telephone wires, generator leads, and power line. The internal detail construction of each unit is shown in Figure 2. Instead of terminating the power cables in potheads, connections to the generators, the station bus, and the power transformers can be made through rigid metal-clad bus duct. A front view of the control and switchgear equipment of a typical plant is shown in Figure 3. This plant is entirely supervised by a voltage relay and load proportioning automatic hydro control.

Paralleling the improvements in switchgear and control arrangements are the improvements in relay design. Leading relay manufacturers now offer a combination of protective relays with multi-contact auxiliary contactors. With these devices considerable panel space can be saved because both devices are mounted in one relay case.

Another simplification is made by the use of "laced" wiring in contrast to formed wiring used almost exclusively in the past. Laced wiring helps to handle the usually great volume of control wires more efficiently. With this new wiring method wires are grouped and "laced" together with cord, sharp bends are avoided, and void spaces within the switchgear structure can be utilized for control wire runs. The neat appearance of laced wires is illustrated in Figure 4.

Unit purchasing cuts first cost

The purchase of a complete set of generating equipment as a unit, including the turbine, transformers, and switchgear, automatically solves most of the coordination problems for the purchaser. Where this method of purchasing is not practicable, the purchase of portions of this equipment in units provides the same savings to a lesser degree. With unit purchasing, the purchaser can be assured that the components within a unit will fit and operate together. The job of specifying station equipment and the coordina-



tion between the various functions during the design and manufacturing stages are greatly simplified. Furthermore, installation costs are far less where the equipment arrives at the site in complete units rather than as loose material.

The modern automatic hydro station provides a long term saving by eliminating constant supervision in the station through the use of remote supervisory control or full automatic control.

A reliable source of station auxiliary power for operation of miscellaneous motors and control is one of the first considerations in setting up a new station. In most small hydro stations an auxiliary power transformer energized from the transmission line provides the necessary auxiliary power when the transmission line is energized. While this arrangement is a compromise because the auxiliary power is not available 100 percent of the time, a sizable saving is made in equipment cost.

The selection of grounding equipment and surge protection generally falls in line with established station practice. However, in fully automatic hydroelectric stations, unusual demands upon the station battery and charger make reliability extremely important. An ample size battery and fully automatic static charger with an adjustable charging rate should be selected. This equipment must be carefully maintained.

Functional diagram helps

The functional diagram shown in Figure 5 gives in detail all the major electrical components that make up the basis for an economically designed hydroelectric plant. The primary protective relay equipment includes the following:

- 3 Generator Differential Relays (87G)
- 3 Station Differential Relays (87)
- 3 Induction-Type Overcurrent Relays (51)
- 1 Three-Phase Current Balance Relay (46)
- 1 Generator Temperature Relay (49)
- 1 Overvoltage Relay (59)

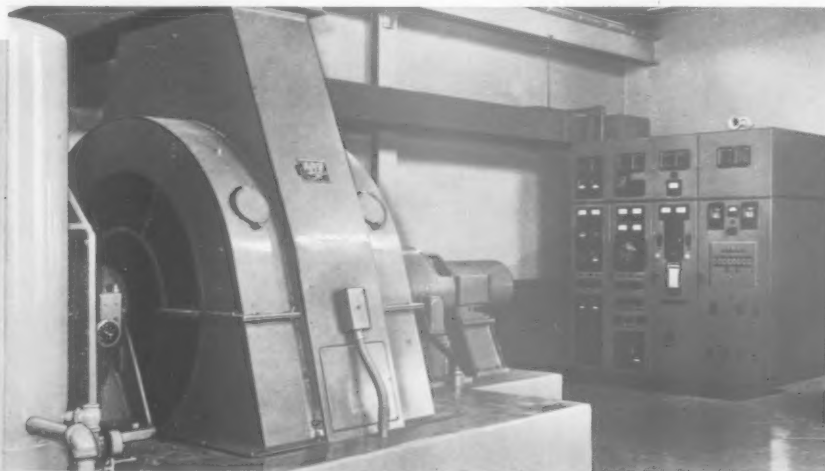
In addition to the above, we list for generator and turbine protection the following relays:

- 1 Generator Field Failure Relay (40)
- 1 Overspeed Switch (12)
- 1 Set of Bearing Temperature Relays (38)

Generator and overall station differential relays, because of their quick action and sensitivity to currents that flow under internal fault conditions, offer the best known type of protection against extensive equipment damage which is due to insulation failure. The differential relays, therefore, should take first place on the list of primary protection relays used in unattended automatic power plants. The cost of these relays is economically justified because of their ability to minimize damage to vital equipment.

The generator windings must be protected against excessive temperature rise. This type of protection is at least as important as differential protection. The temperature sensitive relays may be either of the type operated by secondary windings of the current transformers or may be the bridge type, which is connected to temperature exploring coils placed near the generator windings. The latter type is preferred if the generator is equipped with temperature exploring coils. The action of the relay is based upon the unbalance of a bridge circuit. Unbalance is caused directly by resistance changes with temperature variation of the exploring coils. This relay arrangement is largely insensitive to ambient temperature but wholly dependent upon actual generator temperature. This scheme is very reliable and efficient because the generator can be loaded to the maximum capacity, taking full advantage of the generator short-time overload rating in case of emergencies. In unattended power plants, this relay must be connected to effect automatic shutdown. In a manually operated plant, the exploring coils are either connected through a selector switch to a temperature indicator, or to a temperature relay which may be connected to sound an audible alarm. Temperature protection is usually provided for only the stator windings but may also be provided for the field windings.

A generator overvoltage relay is very desirable for hydroelectric generators for protection against the effects of overspeeding and as back-up protection against failure of the



HYDRO GENERATOR, rated 3000 kva, 2400 volts, 720 rpm, with 15-kw exciter is shown conveniently connected through bus duct to its automatic switchgear control. (FIGURE 3)

voltage regulation equipment. The usual practice is to connect the differential relays (87 and 87G), the overvoltage relay (59), as well as the field failure current relay (40) to a common lockout relay, effecting immediate shutdown of the unit.

A phase current balance relay (46) is needed in order to detect excessive current unbalance, as in the case of an open phase. Under such operating conditions the generator must be disconnected from the system because the damper winding would overheat in a short time.

In the United States it is common practice to provide overcurrent relays for the protection of generators against external faults. The necessity of providing such protection for each generator separately can be questioned when overall station and bus differential protection is provided. If overcurrent relays are employed they should have a voltage restraining characteristic which provides for selective tripping with respect to the distance of a fault from the station.

The functional diagram in Figure 5 shows a second lockout relay (86B) for normal shutdown arranged to disconnect a unit from the line by action of the current balance relay (46) and the bearing thermal relays (38). Normal shutdown as compared with immediate shutdown provides for a gradual transfer of the generator load before the circuit breaker disconnects the unit from the bus or transmission line. This gradual shutdown and lockout condition is desirable because the generator will not overspeed and little overvoltage will be noticeable on gradual load rejection. Unfortunately, this type of shutdown cannot be tolerated upon the operation of differential relays or the generator overvoltage relay.

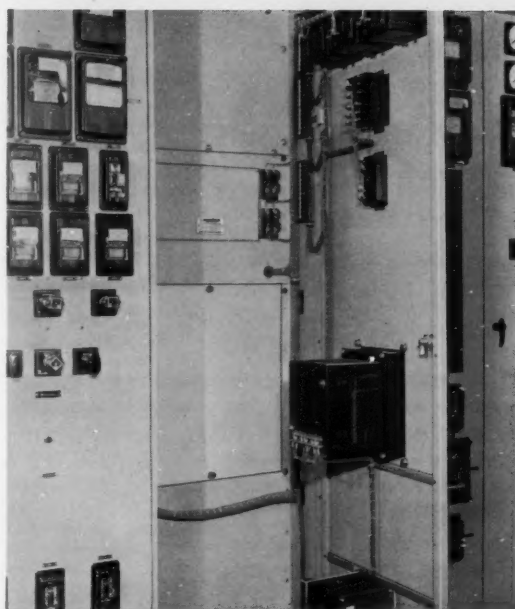
Generator field current failure protection is provided because loss of field current will cause serious transmission line disturbances and overspeeding of the turbine due to loss of the generator synchronizing force. A simple way to detect the loss of field current is by means of an undercurrent relay. The operation of this undercurrent relay justifies immediate shutdown and lockout. Immediate shutdown must be provided in order to minimize the system disturbances, and lockout should be provided.

At least one overspeed switch (12) must be provided to adjust for a turbine speed slightly above the full load rejection overspeed and below the runaway speed of the turbine. The operation of this overspeed switch indicates governor trouble. Normal shutdown and lockout should be initiated by the operation of this speed switch. Normal shutdown and lockout is also recommended in connection with any one of the bearing temperature relays (38) for either the turbines or generators.

Additional protection may be desirable

The following is a list of additional protective relays which may be added to the basic relay set:

- Power Directional Relay (67) (This relay is desirable when a full automatic station is completely unattended.)
- Generator Ground Relay (51G)
- Single or Reverse Phase Relay (47)
- Generator Undervoltage Relay (27)



LACED CONTROL WIRING and convenient terminals facilitate future wiring changes and simplify maintenance checks. (FIGURE 4)

Out-of-Step Relay

Power Transformer Over-Temperature Relay (49T)

A refinement of the protective scheme is accomplished by the addition of this group of relays to the group of basic relays. The necessity for these additional relays is often felt because of individual experience and opinion. The function of each additional relay should be carefully studied, especially with respect to overlapping characteristic with other relays. It is quite possible where relays are not properly adjusted that their function under certain fault conditions becomes erratic. From the standpoint of safety, economy, and continuity of service, a simple compromising relay scheme is often preferred.

Control relays and devices required

The second major group of relays and electro-mechanical devices includes all those which are used entirely for control purposes, or are used to protect control operations.

The governor must be equipped with the following devices:

- 1 Synchronizing Motor (65) with "raise" and "lower" limit switches
- 1 Permanent Magnet Generator for governor fly ball operation, equipped with overspeed limit switches (12)
- 1 Starting Solenoid, the operation of which will open the gate and start the turbine (65S)
- 1 Brake Solenoid with automatic time-delay mechanism (20) and oil pressure valve
- 1 Governor Oil Pressure Relay (63Q)
- 1 "No-Load" gate position switch (33)

1 A motor-operated gate limit control for stations with supervisory control (optional)

1 *Synchro-Operator* device (25) for speed matching purposes

The *Synchro-Operator* device gives short impulses to the governor motor for synchronizing purposes. It functions only when the normal generator voltage is compared with the normal line voltage. Under conditions where the generator has to pick up a dead transmission line, the *Synchro-Operator* device is bypassed with a contact of a so-called "dead bus" relay (83). This relay is set up to override the contact mechanism of the *Synchro-Operator* device.

Pilot exciters may be eliminated

The generator excitation control equipment includes an electro-mechanical, a rotating, or a magnetic amplifier type of voltage regulator. Since the rotating amplifier unit is a part of a separate small motor-generator set, the need for a direct-connected pilot exciter is eliminated.

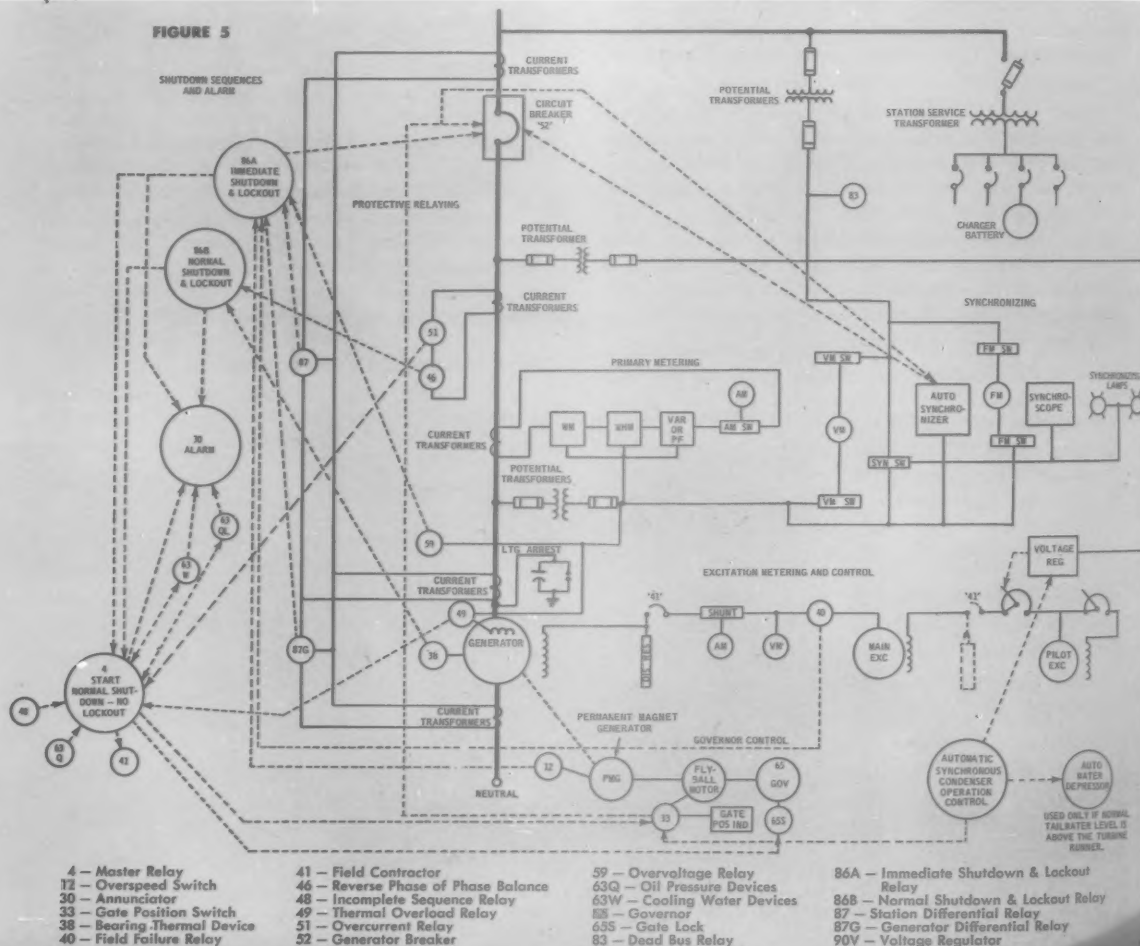
Considerable thought has been given to the elimination of the main generator field contactor and its associated discharge resistor. The possibility of omitting this expensive piece of equipment and replacing it with a main exciter field contactor and main exciter field discharge resistor should not be overlooked. It is true that the generator

field current must be reduced as quickly as possible to zero in connection with differential relay operation. Since differential relay operation is rare, a slight additional time delay may be tolerated. Elimination of the field contactor and control of the generator field current indirectly by means of the main exciter field current introduces such slight increase in the overall time constant that the idea of omission of the field contactor looks very attractive.

Reliable dc needed

A station battery with a rating of not less than 100 ampere-hours and voltage rating of 125 volts dc is generally recommended because most auxiliary control relays are standard for this voltage and contact trouble due to corrosion is unusual in these ratings. Furthermore, the wire size for the relay coils is still reasonably large, so that auxiliary relay coil failure due to copper wire corrosion is unlikely. An undervoltage relay (80) which is adjusted to close its contact and cause immediate shutdown and lockout if the voltage of the battery falls below a pre-set value is very important. Its function provides protection against erratic control relay operation due to low dc station control power.

In very important installations, an auxiliary source of dc control power is provided. This is especially true where supervisory control equipment is dependent upon the station dc control power source. Failure of this source could



knock out the complete supervisory control. There are many automatic control power emergency schemes available to choose from. In general, it is advisable to furnish a separate battery for operation of the supervisory interposing relays and equipment. When a stand-by gas engine generator set is available to furnish the emergency power, one battery may be provided for both the supervisory control and the automatic control relay operation.

Annunciator and alarm used

Two other auxiliary control relay systems must be provided for safe operation. One is a so-called incomplete sequence timing relay. This relay serves as a watchdog to keep an accurate check on the proper function of all relays on an elapsed time basis. The other is a reliable alarm system. In general, a 16-drop annunciator will satisfy all the requirements for system trouble indication. If supervisory control is employed, an alarm indication should be given in the dispatcher's office.

The relays and automatically operated electromagnetic devices, described as primary protective and control relays, satisfy normal requirements except in cases where the station is controlled remotely by supervisory equipment. Regardless of the type of supervisory equipment used, or the method employed in transmitting the control intelligence to the hydroelectric station equipment, a separate set of interposing relays is used to perform each of the following functions, as illustrated in Figure 6.

- a. Start-Stop. (Indicate generator circuit breaker position.)
 - b. Close-Open gate. (Indicate gate position.)
 - c. Raise-Lower generator voltage. (Indicate generator voltage.)
 - d. Raise-Lower gate limit control, if such is provided.
- Note: Automatic gate limit control provides a means for limiting the load of the hydro unit.

The complex nature of supervisory control equipment which is offered by various manufacturers makes it necessary that in each case a special quotation must be obtained. Here again simplification of the general station and distribution layout will pay big dividends. For certain types of equipment, a considerable amount of auxiliary equipment, such as wave traps, etc., is required when a complex distribution system must be controlled.

The introduction of micro-wave control has no particular influence upon the station layout, in general, because all complex functions of electronic equipment are reduced to the control of the interposing relays. The station control, as a whole, is not materially altered. However, special emphasis on the control power source is necessary for operating the supervisory equipment under all operating conditions.

Condenser operation possible

The synchronous machine, normally provided for a hydro station, is capable of operating up to approximately 60 percent of its rated generating kva as a condenser to boost voltage, and 80 percent of its kva to reduce voltage. This limitation is due to field heating and voltage reduction by stability with reduced excitation. The provision for oper-

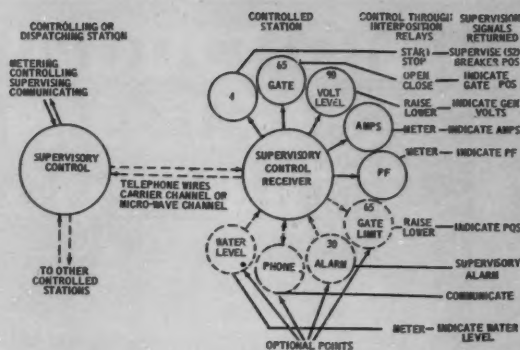


FIGURE 6

ating the hydroelectric station as a condenser substation can be very useful for the purpose of voltage regulation during periods of light loads as well as for providing power factor regulation if the system is supplying large industrial loads. During periods of low water level, when the machine would normally be idle, it can provide a very useful service to the system.

In plants where the normal tail water level is below the turbine runner, synchronous condenser operation becomes quite simple. Under these conditions the machine is brought up to speed and synchronized as a generator, and then the headwater gates are closed, cutting off the driving water power. When the driving power is cut off, the machine drops its generator load and becomes a synchronous motor, with the system supplying the no-load losses. By properly varying the machine excitation, it can be made to draw reactive kva. When condenser operation is planned, additional protection in the form of an out-of-step relay should be provided. The out-of-step relay is the only primary protective relay that is required over and above normal generator protection.

The out-of-step relay will protect the machine from damage caused by overheating of the damper or starting winding, and it also will protect the machine against mechanical resonance of the shaft encountered when the machine is operated out of synchronism. When operating as a condenser with automatic control and voltage regulation, certain conditions frequently prevail which cause operation with a very weak field. This condition increases the possibility of an out-of-step operation. Where supervisory equipment is installed, this out-of-step relay may be eliminated.

In installations in which the normal tail water is above the runner and the advantage of condenser operation is desired, some means must be provided for evacuating this water. If the water is not removed, it will limit the machine's output as a condenser and this additional shaft load may even cause the machine to pull out of step. One means of successfully accomplishing this water depressing is shown in the functional diagram, Figure 7.

When the station is transferred from generation to synchronous condenser operation, a contact-making water level indicator is important. With either manual or supervisory control, water level at the runner is taken into con-

sideration. A high level indication will cause compressed air to be admitted to the sump through a solenoid-operated compressed air valve and force the water down. Compressed air will continue to be admitted until the water is depressed below a point where the low level indicator contact will operate to cut off the air.

If the water is not depressed below the high level point within a given time, a failure of the depressing equipment is indicated and contacts can be arranged to shut down the machine. These contacts should not cause a lockout, however, since the machine can still be operated as a generator.

With the water below the runner, the turbine blade is free to turn in air. Should the water again rise during condenser operation, it is permitted to rise to the mid-level point before any action is taken. At this point, the solenoid operates to admit air and push the water down again. Air will be admitted until the level is below the low level point. Operation in this manner will prevent unnecessary oscillatory or so-called pumping action of the solenoids. Should the water continue to rise, the machine will shut down when the water again reaches the high level point.

Instead of a water level indicator, float switches, electrode-operated relays, or any other means of electrically detecting water level may be used. The scheme described requires the use of three liquid level relays, two auxiliary relays, and a timing relay for operation.

In a manually operated plant, a control switch can be used to initiate the operation of this equipment. In a supervisory or remote control plant in which gate position is controlled, a normally open circuit breaker auxiliary switch and a zero gate position switch can be used to perform this function. Normal plant installations fre-

quently require compressed air equipment with sufficient capacity to take care of the water-depressing requirements as well as other uses. The cost involved for water-depressing equipment may be less than the expense involved in building a powerhouse with the tail water below the turbine runner level. Condenser operation under certain circumstances is so important that the additional expense of water-depressing equipment is justified.

Metering needs filled

Since nobody is present to read meters except when the station is operated manually, the number of indicating instruments in an automatic hydroelectric station can be reduced to a minimum. Therefore, in order to conserve panel space and reduce expenses, a small size meter such as a 4½-inch square-type switchboard meter is generally recommended. Where indoor equipment is used, the necessary current transformers and potential transformers for these indicating meters are usually provided as part of the switchgear equipment. The following meters are usually required:

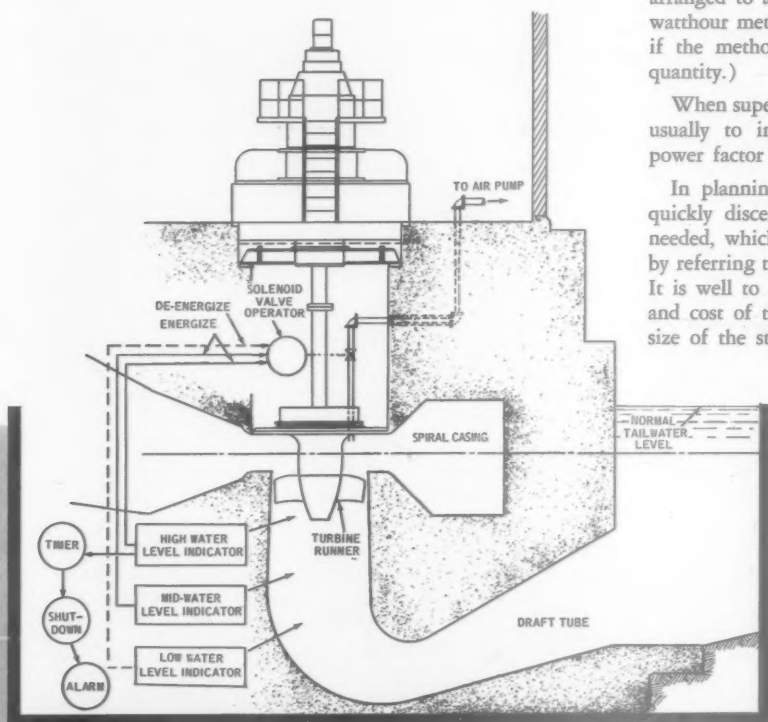
- 1 Generator Wattmeter
- 1 Generator Reactive Volt-Ampere Meter or Power Factor Meter
- 1 Generator Ammeter and Phase Selector Switch
- 1 Voltmeter and Transfer Switch
- 1 Synchroscope
- 1 DC Field Ammeter and Shunt
- 1 DC Exciter Voltmeter

Sometimes these additional meters are specified:

- 1 Water Level Recorder
- 1 Watthour Meter
- 2 Watthour Meters with ratchets if the generator is arranged to act as a condenser at certain times. (These watthour meters may be supplemented by varhour meters if the method of keeping station records includes this quantity.)

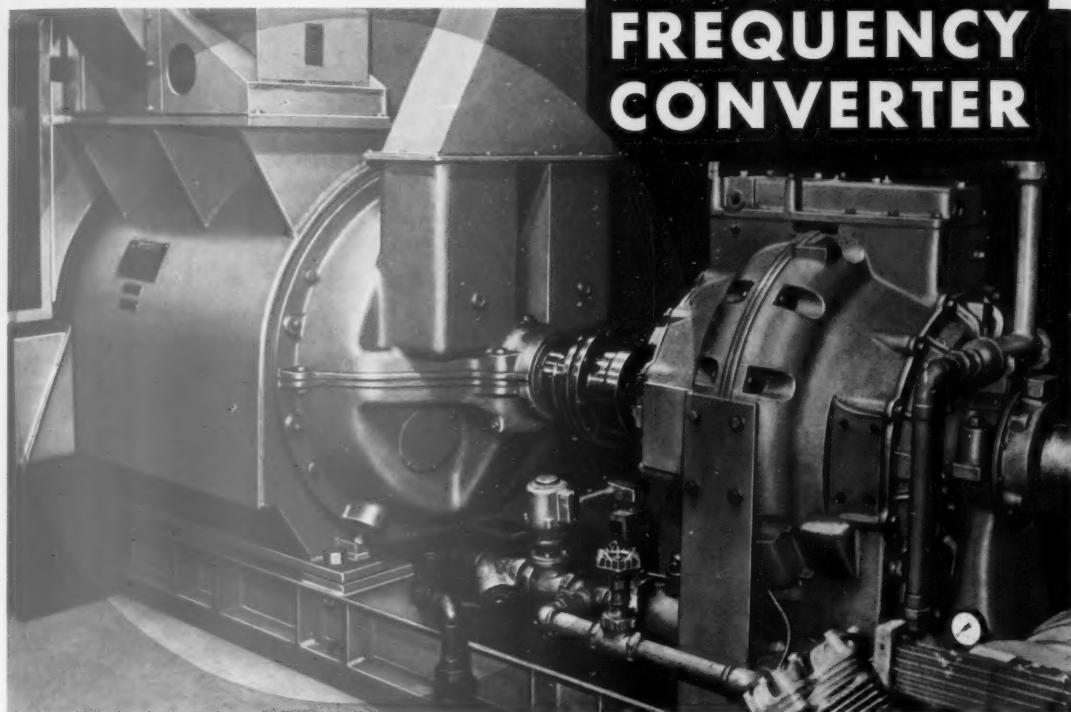
When supervisory equipment is furnished, it is arranged usually to include water level, generator current, and power factor indications.

In planning a hydroelectric station, the engineer can quickly discern which features and devices are actually needed, which are refinements and which are pure frills by referring to a simple functional diagram of the station. It is well to remember that each device adds to the size and cost of the switchgear and may increase the overall size of the station.



WATER DEPRESSING equipment need for synchronous condenser operation is dictated by tailwater level conditions. Standard control devices assure its reliability. (FIGURE 7)

Characteristics of the... **INDUCTION FREQUENCY CONVERTER**



FREQUENCY IS CONTROLLED by dissipating shaft losses in the water-cooled eddy current brake at right.



by **R. C. MOORE**

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Allis-Chalmers Mfg. Co.

Supplying variable frequency output from its slip rings, this converter is essentially a wound-rotor induction motor.

THE WOUND-ROTOR INDUCTION MOTOR is widely used because speed change is easily obtained by varying an external resistance electrically connected to the rotor. Slip rings are necessary to dissipate resistance losses outside the motor and to simplify resistor step adjustments. In applications of this type, the power delivered by the motor shaft is of principal interest. Rotor resistance losses are incidental and tolerated in order to obtain speed variations.

However, if the power in the rotor circuit is utilized instead of wasted in resistors, the converter principle of the induction motor is obtained. The induction frequency converter, then, is a wound-rotor motor in which the power delivered by the rotor through the slip rings is of principal interest. The output at the shaft is incidental and is toler-

ated to obtain slip-ring power of variable voltage and frequency. When speaking of converter watts, kw, or horsepower output, reference is made to slip-ring output.

Converter action

When the stator winding of the converter is connected to a power supply of constant voltage and frequency, a rotating magnetic field is set up in the air gap and induces voltage in the rotor winding. At standstill the frequency of this induced voltage is the same as that of the stator, and its magnitude depends on the design value of turns ratio between the stator and rotor windings.

If the rotor runs at small slip, 10 percent for example, the induced voltage and its frequency are each 10 percent of their standstill values. Should the rotor be driven full speed backwards against the magnetic field, that is, at 200 percent slip, the induced voltage and its frequency are twice their standstill values. The frequency at which the converter delivers power is therefore determined by the slip of the rotor with respect to the rotating magnetic field. Induced rotor voltage and frequency are dependent upon rotor speed, while the ratio of induced rotor voltage to its frequency is constant regardless of rotor speed.

In addition to frequency conversion, phase conversion can also be obtained, since the converter rotor can be wound for the number of phases desired. Ordinarily this is of academic interest only, since three-phase windings are most common.

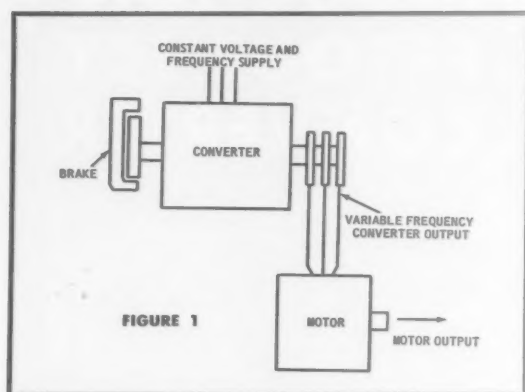


FIGURE 1

Diagrammed in Figure 1 is a converter supplying power to a motor. Also shown is a shaft brake which holds the converter rotor speed constant so that the desired voltage and frequency will be maintained. Any suitable device may be used instead of the brake to obtain the desired converter rotor speed. For example, a direct current machine could be used to absorb or supply power.

When a brake is used the highest converter frequency that can be obtained is equal to the stator frequency. If a direct current motor is used instead, and drives the converter backwards, then converter frequencies higher than the stator frequency can be obtained. For simplicity, converter operation and characteristics discussed here are based on the brake method indicated in Figure 1.

Converter voltage regulation

When the converter supplies power to a motor its slip-ring voltage is less than the induced rotor voltage because the load current of the motor causes impedance drops in the converter. Since increased motor current results from increased motor torque, it is convenient to show in Figure 2 the variation in slip-ring voltage as a function of motor torque.

The data shown in Figure 2 is for the 2-pole dynamometer motor described in a recent issue of the *Electrical*

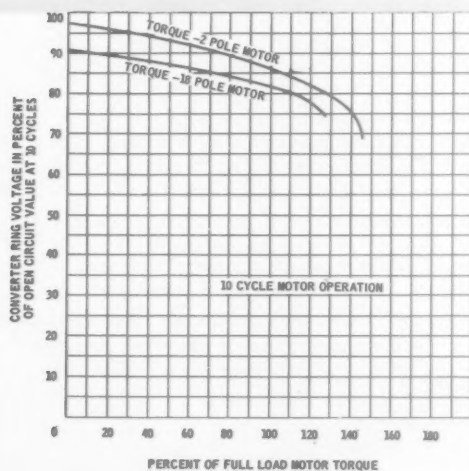


FIGURE 2

*Review*¹. The dynamometer motor is of the low reactance type and has the high power factor characteristics of an induction motor with a small number of poles. The other curve shown in Figure 2 is for an 18-pole squirrel-cage type induction motor of the same horsepower rating (900 hp at 54 cycles) as the 2-pole dynamometer motor. The calculated curve for the 18-pole machine offers a comparison of the effects of low power factor loads on converter voltage regulation. For a given horsepower, induction motors with a large number of poles have inherently lower power factor than those with a small number of poles.

Converter frequency

The frequency of the converter output voltage and current depends directly on rotor speed and is constant so long as the shaft speed is constant. Converter frequency in cycles per second is simply the stator frequency times the percent departure of the rotor from synchronous speed.

It has been pointed out that voltage changes occur at the slip rings when the load current changes. However, there is no accompanying variation in frequency. The rotor speed alone determines the frequency output of the converter.

Effects of poor voltage regulation

The breakdown torque of an induction motor varies as the square of its terminal voltage, and the pull-out torque of a synchronous motor varies directly with its terminal voltage. Either type of motor receiving power and current from the converter slip rings might not carry overload satisfactorily if the converter voltage regulation is poor. The use of a synchronous motor load for the converter may be considered when it is desirable to improve the converter regulation and stability.

The considerable effect of voltage on induction motor torques is shown in Figure 3 for the 18-pole motor previously considered. Power is supplied by a converter having good electrical and magnetic characteristics. The defect in operation is due to the induction motor load having low power factor. Operation at 10 cycles would

1. "Variable Frequency Dynamometer," E. H. Fredrick and M. F. Gay, *Allis-Chalmers Electrical Review*, Fourth Quarter, 1952.

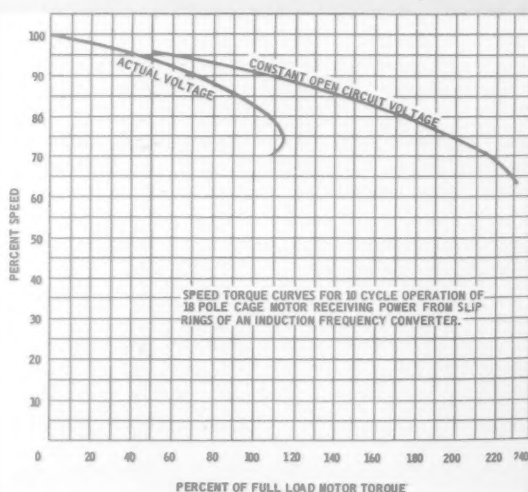
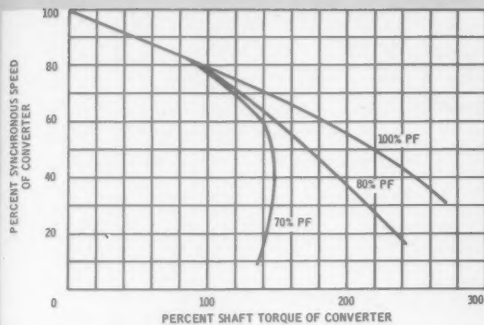
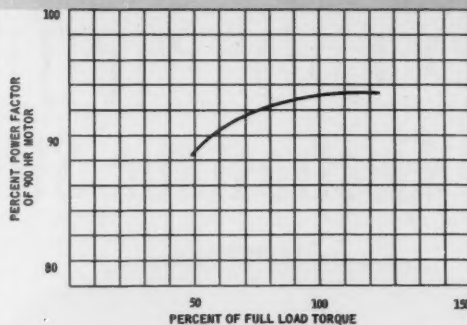


FIGURE 3



STABLE CONVERTER OPERATION requires the high maximum torque available at high power factor loads. (FIGURE 4)



AT 54-CYCLE constant voltage input, the 900-hp, three-phase, 2-pole induction motor has this power factor characteristic. (FIG. 5)

hardly be practical with such a low value of breakdown torque. For example, a slight dip in the normally constant voltage applied to the converter stator winding would cause a reflected drop in the slip-ring voltage and a stalling of the 18-pole motor on a constant torque load. Voltage regulation is important to insure successful operation of the motor receiving power at variable voltage and frequency from converter slip rings. However, the converter itself is a wound-rotor induction machine and as such has its own stability limits, that is, its own breakdown torque characteristics.

Converter stability limits

Some shaft braking torque will be required at all times to hold the converter shaft at a constant speed and maintain constant frequency output. This braking torque will vary as the power drawn from the converter slip ring varies. In other words, the converter shaft has torque speed characteristics like a wound-rotor motor.

As expected from induction motor theory, the maximum or breakdown torque value of the converter shaft output remains unchanged when the converter load is entirely resistive. But if a low power factor load is supplied by the converter, the breakdown torque is reduced as shown in Figure 4. It can be demonstrated that the converter slip-ring kw output at constant frequency is directly proportional to its shaft torque. The derivation is as follows:

Converter kw slip-ring output =

$$\text{Converter shaft kw output} \times \frac{s}{1-s} =$$

$$\text{Converter shaft kw output} \times \frac{sN_o}{(1-s)N_o} =$$

$$\text{Converter shaft kw output} \times \frac{sN_o}{N}$$

$$\text{Converter shaft kw output} = \frac{TN}{7040}$$

$$\text{Then, converter kw slip-ring output} = \frac{sN_o}{7040} T = KT$$

Where s = rotor slip of converter, per unit.

N_o = synchronous speed of converter in rpm.

$N = (1-s)N_o$ = actual converter rotor speed in rpm.

T = converter shaft torque, in ft-lbs, to hold rotor speed at value to maintain frequency.

$$K = \text{proportionality constant} = \frac{N_o}{7040}$$

POWER FACTOR at the converter input is influenced by the power factor of the converter load. (FIG. 6)

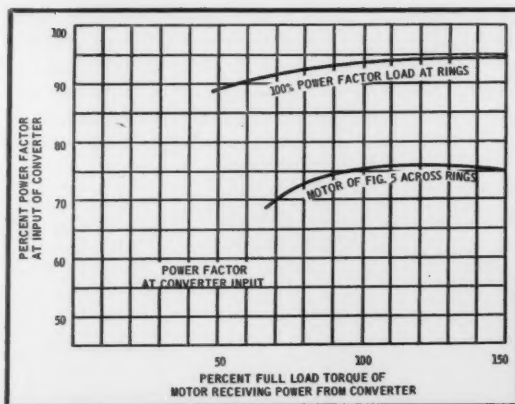
Figure 4 indicates that low power factor loads reduce the maximum torque for stable converter operation. Maximum converter kw output is reduced as shown in the formula derivation. The conclusion, then, is that induction frequency converter loads should have high power factor characteristics.

Effect of load power factor

Power factor characteristics shown in Figure 5 are those of a 2-pole dynamometer motor. This motor, when connected to the converter slip rings, introduces an impedance which is made up of both resistance and reactance.

One effect of this load reactance is that reactive volt-amperes must be supplied from the main power supply line to the primary winding of the converter. Because of this, power factor measured at the converter input depends on the power factor of the load at the slip rings. Figure 6 compares calculated data for a unity power factor motor with the curve from Figure 5 and indicates the effect of these slip ring loads on the power factor at the converter input. Evidently, if a synchronous motor alone were supplied by the converter, it would be possible to supply the converter inherent reactive volt-ampere requirements so that unity power factor could be obtained in the power line to the converter.

For applications requiring accurate regulation of variable speeds within a specified range of relatively low shaft speeds, the induction frequency converter is very practical. Although the induction frequency converter is essentially a wound-rotor motor, design and construction modifications are necessary, and these modifications depend upon the specific application. Careful consideration must be given the converter design to assure a system that will operate successfully.



PLOTTING Electrostatic Stress



Graphical and experimental methods are combined in this procedure which requires only a simple laboratory setup.



by **G. E. JANSSON**
and **WILLIAM HARPER**
Allis-Chalmers Mfg. Co.
Boston Works

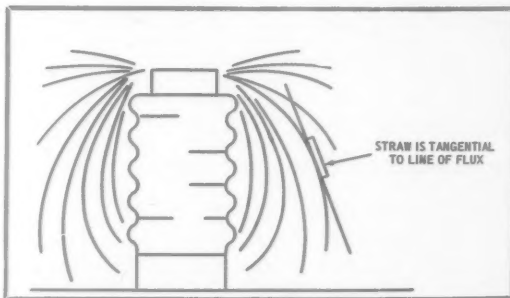
TRENDS TOWARD HIGHER TRANSMISSION VOLTAGES and reduced physical size of power apparatus have emphasized the need for accurate dielectric design of high voltage apparatus. While the design is still on the drawing board, voltage gradients and field distribution that will occur in any insulating body at test or operation voltages must be determined. The method given here combines both experimental and mathematical analyses of the insulating body for the solution of dielectric design problems.

Most experimental methods used for plotting electrostatic fields require extensive laboratory equipment and may require elaborate models. The dielectric needle method of plotting electrostatic fields requires very little apparatus

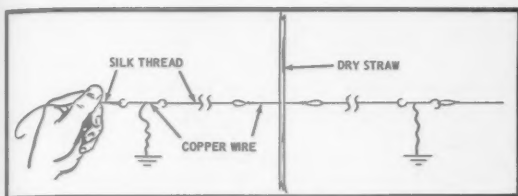
outside that normally found around a high voltage laboratory, and the technique used is very simple. This method is based on the fact that a needle-shaped piece of dielectric material is polarized when it is placed in an electrostatic field. If free to rotate about its axis, the dielectric needle tends to align itself tangentially to the field flux which is also the line of dielectric stress, as shown in Figure 1. Any lightweight dielectric material will suffice; a common straw can be used.

Dielectric needle method of electrostatic field plot

The field plot is made by applying a high voltage to the electrodes of the apparatus to be studied, and suspend-



FREE TO ROTATE about its axis, the dry straw becomes polarized and aligns itself with the field flux. (FIGURE 1)



AS A SAFETY MEASURE the dry straw and the copper wire on which it rotates are isolated from the operator by silk or nylon threads and a grounded copper wire. (FIGURE 2)

ing the needle in the electrostatic field which is established between the electrodes. The angle of the straw is recorded to establish the direction of the field flux at that point. A dielectric needle can be used for electrostatic field plots in homogeneous fluid insulating bodies (consisting of only one dielectric material) at any voltage up to the corona or flashover voltage of the apparatus. Accuracy is high if the needle and its fulcrum are made small in size to minimize distortion of the field.

When recording lines of flux, a single light in a dark laboratory was used to project a shadow of the insulator and the straw onto a paper screen, and the shadow of the straw was traced to record the field plot. In adapting this method for later use, a box camera was designed to eliminate work with high voltage in a darkened laboratory. The field plot is recorded by tracing along the straw's image projected onto a piece of tracing paper mounted on ground glass in the camera's focal plane. The picture at the top of the preceding page shows the camera in use during a field plot.

Flux line elements at large distances from the electrodes and in open spaces are plotted with a straw 2 inches in length. These lines may be supplemented by using a $\frac{1}{2}$ or $\frac{3}{4}$ -inch straw to plot the field in close quarters. Since forces of a very small order are exerted on the needle, great care must be taken in mounting it if accurate results are to be obtained.

To assure smooth, free rotation of the straw about its axis, a pivot hole is burned through it, and the straw is balanced as accurately as possible about the pivot point. Silk or nylon thread, used to suspend the needle and its fulcrum, must be long enough to assure adequate insulation and protection for the operator. Special care should be taken to keep the thread clean and dry. As a safety measure, the end of the thread is connected to a section of copper wire which carries a ground connection, and an extension of insulating thread is added between the grounded wire and the operator, as shown in Figure 2.

Two operators are ordinarily required to manipulate the straw, one at either end of the thread. If the insulator is small, one end of the thread may be made fast and the straw manipulated from the other end of the thread without seriously affecting accuracy. A field plot as it comes from the laboratory is shown in the right half of Figure 3.

THE FIELD PLOT is a completion of the flux line elements, shown at far right, drawn in the laboratory. (FIGURE 3)

Each mark represents a flux line element giving the direction of the field at that point. The left side of the figure shows the field plot after completion. A "reference library" of field plots has been compiled over a number of years, and field plots for a large number of electrodes having various sizes and shapes are available for use in preliminary design work.

The field plot serves two purposes. First, it indicates points of field concentration where high voltage gradients occur; second, it provides a means of checking the equipotential plots because field flux lines and equipotential lines intersect at right angles.

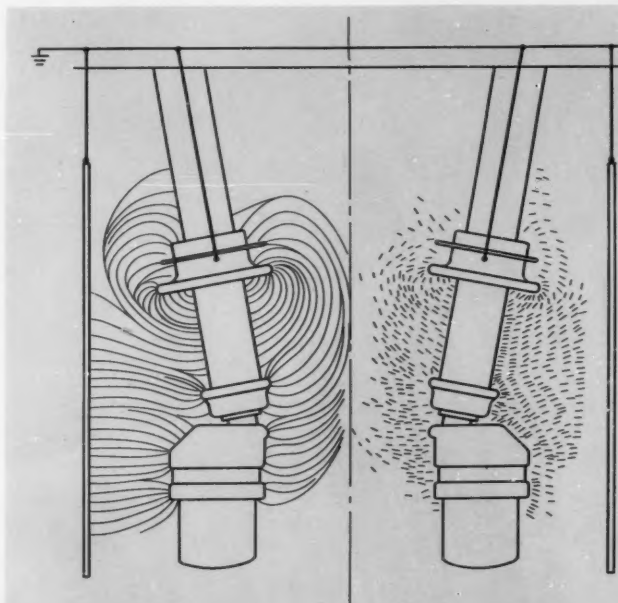
Basis of mathematical analysis

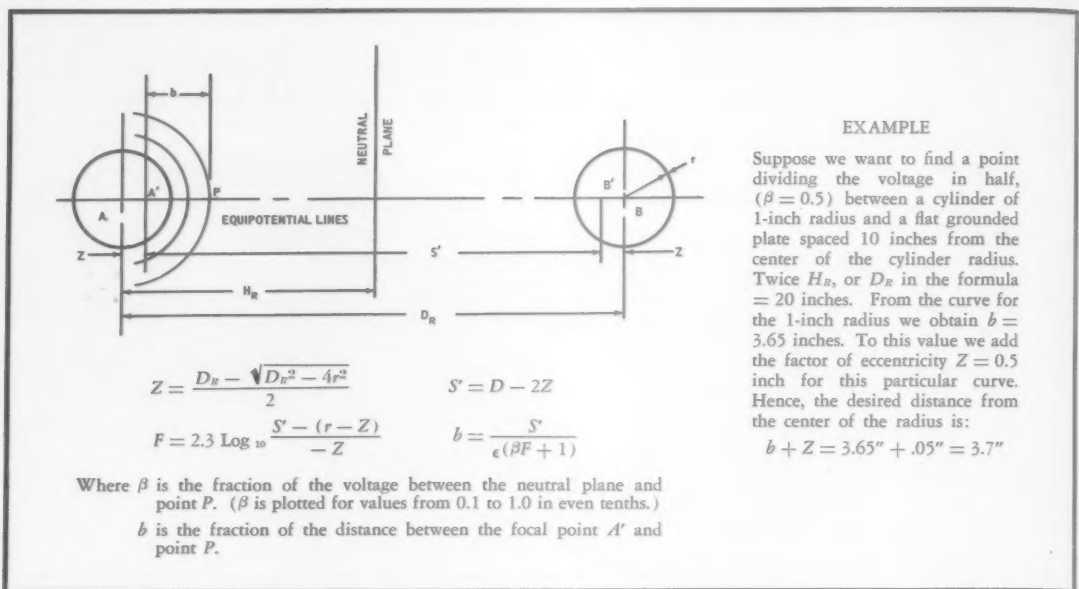
Mathematical analysis of irregular electrodes, such as those used in circuit breakers, is extremely complex unless some assumptions are made to simplify the procedure. Calculation of voltage gradients and the graphical method used to plot equipotential lines are based on analysis of the electrodes in terms of cylindrical elements. Potential distribution is plotted in a plane perpendicular to the cylindrical element axis on the assumption that element length is great compared to the thickness of the plane. Since breaker electrodes are curved in two planes 90 degrees apart, the end effect of the cylindrical element may be neglected.

Making the equipotential plot

A point of given potential between two cylinders, or between a cylinder and a plane, may be located from a series of formulas given in Figure 4. Figure 5 illustrates their application to typical circuit breaker electrodes.

When the potential distribution is plotted between an electrode at line potential and the grounded tank, the tank is assumed to be a "neutral plane" midway between the electrode and its image of the opposite potential, which



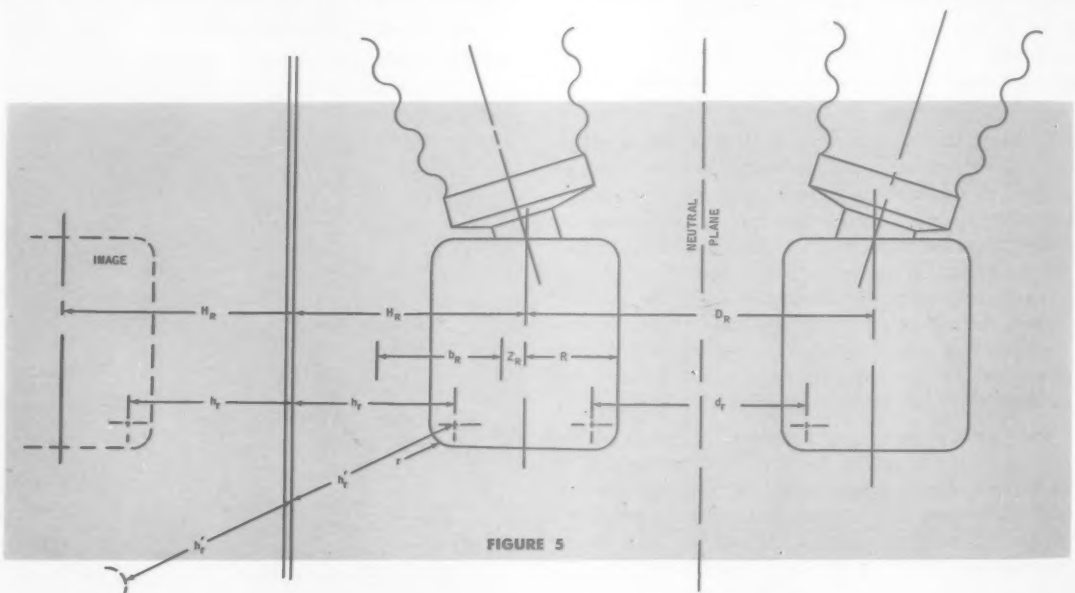


is projected an equal distance on the other side of the tank. Equipotential lines are plotted by dividing the voltage into ten equal parts to establish ratios of " β " in even tenths (see Figure 4). Point P is plotted for values of " β " ranging from 0.1 to 0.9 in a series of locations throughout the insulating body. Points of equal voltage are connected to give approximate equipotential lines.

To reduce the time required for locating points at any given potential a set of curves has been plotted from the

cylindrical formulas. Figures 6 and 7 show two sets of these curves, one set includes radii r from .25 inch to 7 inches, the other, spacing D from 5 inches to 80 inches. The complete set covers most of the electrodes used in circuit breaker design.

Lines plotted in this manner are of acceptable accuracy in all but the most irregular portions of the insulating body. In those areas, the equipotential lines are modified to agree with field plots made previously on similar elec-



Use of the combined plots in design

Figure 9 shows a combined field and equipotential plot for the preliminary design of one pole unit of a breaker in the closed position. Equipotential lines are noted with the potential that would occur during the NEMA 60-cycle, 1-minute high potential test. A similar plot is made with the breaker in open position. Voltage gradients are calculated directly for points that are indicated to be critical, and electrode shapes are modified to assure that corona gradients occur only at voltages well above the normal operating voltage of the apparatus.

An attempt is made to maintain a balance of dielectric strength throughout the insulating body to attain the greatest possible overall strength within a given size tank or cubicle. Highly stressed gaps, which tend to draw impurities from the oil to form "bridges" that may cause dielectric breakdown, are eliminated. In the design of circuit breakers for upper voltage classes, the interrupting

units are enclosed in smooth, well-rounded metal shields to provide electrode shapes which more nearly approach the ideal configurations of spheres or cylinders of large radii. This reduces dielectric stress at points which tend to give trouble on the 1-minute high voltage test and during long periods of time at operating voltage.

Preliminary field plots and potential diagrams of a new design made early in the layout stage have enabled a prediction of the actual field distribution and voltage gradients under test with less than 5 percent error. Thus costly and time consuming design changes after the breaker has been built are avoided.

This combined graphical and experimental method has been found to be a practical tool for circuit breaker design. It involves only simple mathematical analysis and laboratory equipment, yet gives results well within the limits of accuracy imposed by manufacturing tolerances and the variations in dielectric quality of insulating materials.

THE FIELD INTENSITY or voltage gradient at any point X can be calculated with these fundamental formulas.

If the point is between two cylindrical conductors in a homogeneous medium:

$$\left(\frac{dv}{dr}\right)_X = \frac{E}{r_x \log \epsilon \left(\frac{d}{r}\right)} \text{ volts/cm}$$

If the point is between a cylinder and a plane:

$$\left(\frac{dv}{dr}\right)_X = \frac{E}{b_x \log \epsilon \left(\frac{2b}{r}\right)} \text{ volts/cm}$$

Where E is the potential in volts applied between the conductors;

r_x and b_x are the distances in centimeters from point X to the center of the cylindrical electrode or surface of the plane at zero reference potential.

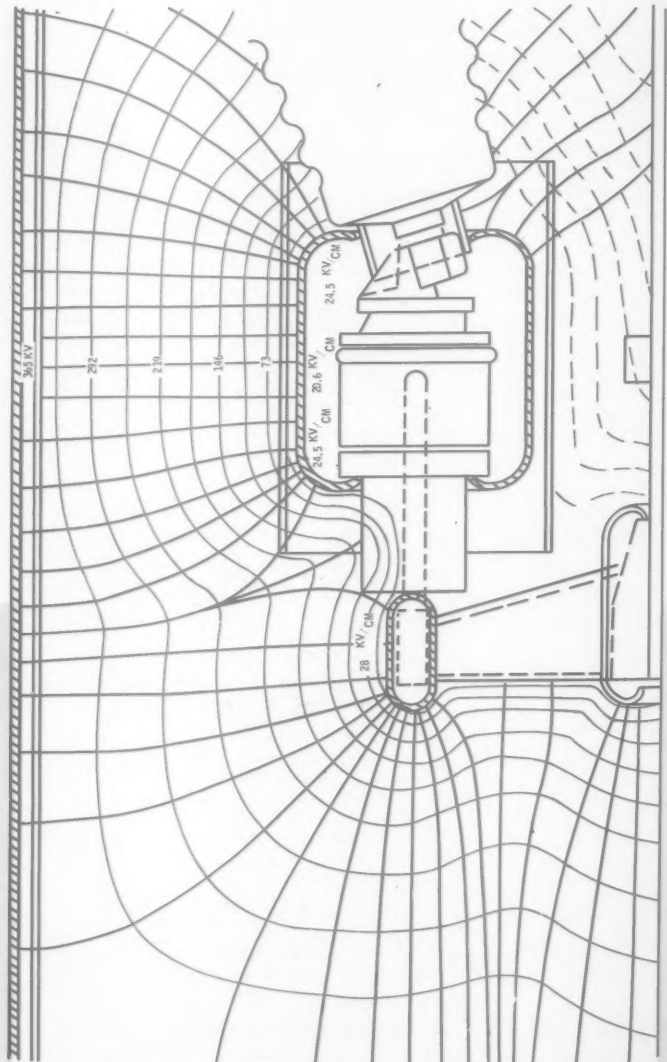
r is the radius in cm of both cylinders,

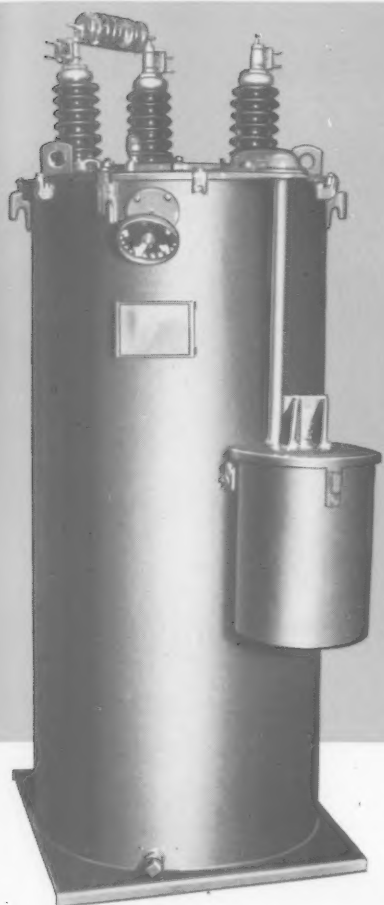
d is the distance in cm between centers of the cylinders,

b is the distance in cm from the plane to the center of the cylinder.

FIGURE 8

EQUIPOTENTIAL LINES, shown in green, and the field plot for one breaker pole in closed position are combined in this diagram. (FIG. 9)





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